4

# Geomagnetically Induced Currents and its Presence in the Eskom Transmission Network

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*"The most beautiful experience we can have is the mysterious. It is the fundamental emotion which stands at the cradle of true art and true science.*

*Whoever does not know it and can no longer wonder, no longer marvel, is as good as dead, and his eyes are dimmed."*

- Albert Einstein, 1931 [4]

# Terms of Reference

This project was commissioned by Mr A C Britten of Eskom TSI and supervised by Prof. C T Gaunt of the University of Cape Town. The final instructions given on 1 February 1999, were:

1. To undertake a thorough literature search on the mechanism of Geomagnetically Induced Currents and its effect on power network equipment.

2. Review prevailing solar activity and identify the potential benefits of monitoring GICs and its effects.

3. Investigate correlation (if any) between previous system events and geomagnetic storms.

4. Understand the modelling process necessary to theoretically predict expected levels of GIC in the Eskom MTS.

Instruction 3 was necessary to establish whether the Eskom MTS might be susceptible to GICs. Instruction 4 was done based on a method developed at the Finnish Meteorological Institute. The final thesis reflects work for all four instructions.

# Declaration

This thesis could not have been carried without substantial help from expertise from the University of Cape Town, Eskom and the Finnish Meteorological Institute, all whom have been mentioned in the acknowledgements. The breakdown of work on various aspects of the thesis was as follows:

**Literature Search**

Although the literature review was done by myself I would not be able to do it thoroughly without the input and guidance of Prof. C T Gaunt (UCT), Mr A C Britten (Eskom, TSI), Prof. R Pirjola (Finnish Meteorological Institute) and Mr C King (Eskom, Transmission).

**Investigation of Past Events**

The investigation into possible correlation between system events and GICs would not be possible without data received from Dr P Sutcliffe (Hermanus Magnetic Observatory) and Mr E Stokes-Waller (Eskom, National Control). Guidance to identify such events was provided by Prof. C T Gaunt (UCT).

**Modelling Technique**

The understanding and application of the necessary method to completely model the effect of GICs on power networks would not be possible without the support and guidance of Prof. R Pirjola and Dr A Viljanen both of the Finnish Meteorological Institute.

Signature: Signed by candidate Date: 28/02/2000

# Abstract

This thesis serves to describe the findings of the investigation into the possible existence and occurrence of Geomagnetically Induced Currents (GICs) in the Eskom MTS. The project commenced in January 1999 and is a joint collaboration between Eskom, the University of Cape Town and EPRI.

Eskom has been aware since about 1990, that occasional severe geomagnetic storms in the Southern Cape might disrupt the MTS in that area. At that time no correlation was observed between disruptions at selected sites of the Eskom MTS and geomagnetic activity. (The sites selected were based on the knowledge at that time.) However, there is now evidence that the sites most susceptible are not at the conventionally accepted locations, and that damage and disruption may have occurred where it was not expected.

For this project a thorough literature search was done to understand the source and effects of GICs. An investigation was conducted into the past events on the Eskom MTS, which was compared with geomagnetic activity to check for correlation. Finally, the modelling process of a network that would indicate its susceptibility to GICs was studied.

Typical disruptions that would indicate the existence of GICs include Buchholz trips, interwinding faults, permanent failure due to internal faults, etc. From this investigation there is circumstantial evidence that equipment damage may have occurred due to geomagnetic activity during the previous solar cycle peak

# Acknowledgements

I am indebted first and foremost to my supervisor, Prof. Trevor Gaunt for his guidance and support with the project. His numerous discussions, advice and comments have greatly helped me in the course of this work.

I owe many thanks to Mr Tony Britten of Eskom TSI who approached me with this project. I appreciate the opportunity he gave me as well as his interest and support of the project.

My sincere appreciation goes to Prof. Risto Pirjola and Dr Ari Viljanen of the Finnish Meteorological Institute for their help and support. Prof. Pirjola went out of his way to help and guide me; his patience and friendly support is greatly appreciated.

I own many thanks to Mr Colin King of Eskom Transmission for our many discussions and his comments. I would also like to thank Dr Peter Sutcliffe of the Hermanus Magnetic Observatory. Dr Sutcliffe was always available to discuss and provide information regarding geomagnetic disturbances. Mr Edmund Stokes-Waller of Eskom National Control supplied the data on past system events, which is greatly appreciated. I also own thanks to Mr Archie Graham for providing help with illustrations and software.

This project would not be possible without the financial support of Mr Logan Pillay (Eskom TSI) and the Eskom Transmission Group Steering Committee for which I am very grateful.

I wish to express my gratitude to my parents for their continuous support and to my fiancée Willina, who has been a constant source of encouragement through the many years of my studies.

Above all my eternal gratitude for the love that transcends all understanding bestowed on me by God the Father, the Son and the Holy Spirit.

# Contents

# List of Illustrations

# Introduction

During solar storms, enormous flares of energy on the sun's surface hurl dense waves of charged particles through space. These emissions are called Coronal Mass Ejection's (CME's) and the flow of plasma, called the solar wind, may reach the earth several days later, where it interacts with and disrupts the earth's magnetic field, known as a geomagnetic storm.

It has been known since the early 1940's that large transient fluctuations of the earth's magnetic field can produce quasi-dc currents in electric power systems through the grounded neutral of transformers. These geomagnetically induced currents (GICs) cause half-cycle saturation of power transformers resulting in increasing reactive power requirements and the generation of harmonics. During intense geomagnetic disturbances there have been unusual swings in real and reactive power flow, excessive voltage fluctuations, frequency shifts, undesired relay operations, and high harmonic currents [1, 2, 3].

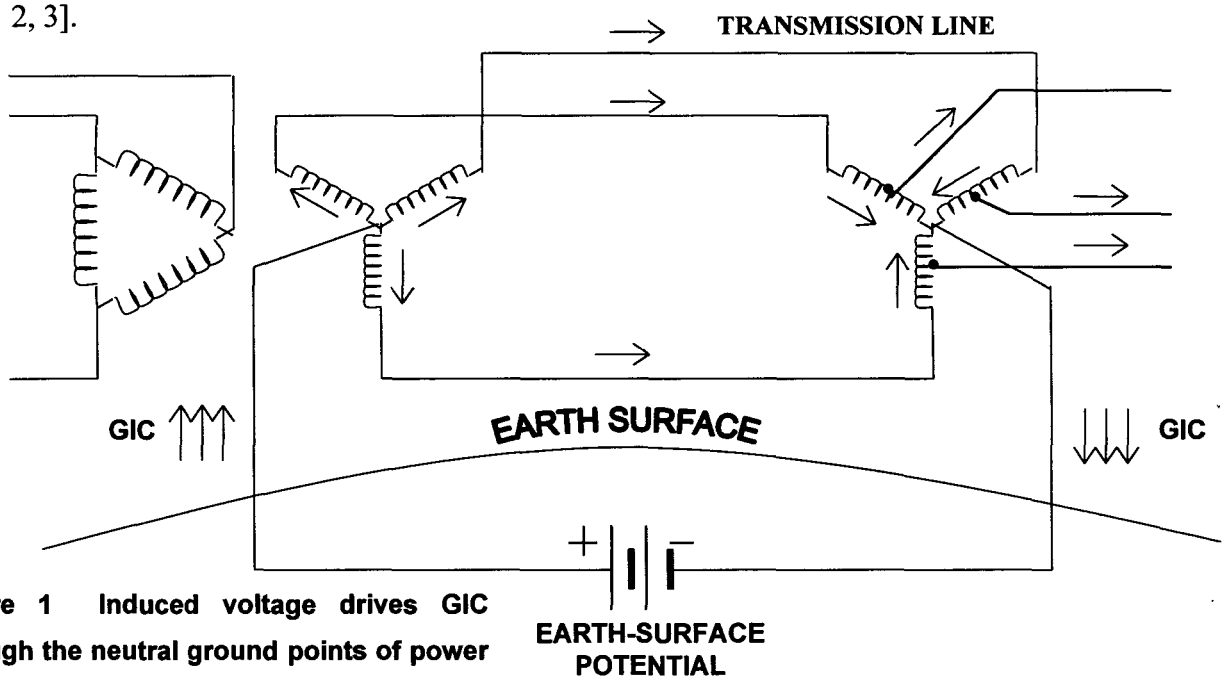


**Figure 1 Induced voltage drives GIC through the neutral ground points of power transformers.**

The most dramatic recent impact occurred in March 1989 with Solar Cycle 22 when virtually the entire Canadian province of Quebec was plunged into darkness. In total 21500 MW of load and generation was lost and it lasted more than 9 hours to fully restore the supply. The same geomagnetic disturbance affected several large power transformers elsewhere, and caused hundreds of maloperations of relays and protective systems. Power systems suffered voltage depressions and unusual swings in real and reactive power flow [1, 3].

Power networks are more vulnerable today because of the continual expansion and increase in interconnections, thus linking large cumulative earth surface potentials. Networks situated above igneous rock geology are most vulnerable since the relatively high resistance encourages more current to flow in alternative conductors such as the power lines located above these formations. Power systems adjacent to coastal areas are also more susceptible to GICs due to the large induced currents in the highly conductive seawater.

The greatest GIC problem occurs at high latitudes in or near the auroral zones. In these areas the geomagnetic storms are most intense and frequent since the ionospheric source is typically a localised electrojet. The occurrence of these storms statistically follows the sunspot cycle (ca. 11 years), so definite and reliable conclusions of GICs require recordings and observations of at least this time. Countries at mid-latitude such as South Africa are located far from the magnetic pole and therefore do not experience the same severity of geomagnetic disturbances as North America or Scandinavia. However, long transmission lines, high resistance rock geology and coastal areas could present a risk during a very severe storm. This project serves to introduce the phenomenon as part of Eskom's preparation for the next solar peak. The solar peak is expected in the first quarter of 2000 with intense geomagnetic activity expected in the 3 following years.

# Chapter 1

# Geomagnetic Storms

## 1.1 Introduction

Coronal mass ejections are violent discharges of electrically charged gas from the Sun. Such an explosion can hurl up to 10 billion tons of gas into space at up to three million kilometres per hour [11]. Particles from solar flares disrupt power systems, communication technology, space technology etc. The radiation from the flares can even give passengers in aeroplanes a dose of radiation equivalent to a medical X-ray [12].

On March 13, 1989 a severe geomagnetic disturbance occurred affecting various technology systems worldwide. This was due to a gigantic solar flare that erupted from a large sunspot only three days earlier. Within two days, massive amounts of protons and electrons from the blast was captured by the earth's magnetic field, producing brilliant auroras and disrupting electric power systems, orbiting satellites and communication systems.

The March 13 geomagnetic storm caused more havoc on U.S. and Canadian power systems than any other in history did [4]. Some of these disturbances include the blackout of the entire Hydro-Quebec power system, severe damage to large power transformers and hundreds of misoperations of relays and protective systems. Power systems also suffered voltage fluctuations and unusual swings in real and reactive power flow. Transformers were damaged by severe tank heating and melted copper conductor

well as everyday experience, he failed to convince his principal successors. Only in 1510 did Nicolaus Copernicus (1473-1543) began work on a sun-centred system and went far beyond Aristarchus by providing detailed models of the revolution of planets around the sun.

According to his law of centripetal force, Isaac Newton (1642-1727) estimated the mass and density of the sun. While his initial estimate of the sun's mass turned out to be too small by an order of magnitude, his result for the sun's relative density was within 2 percent of the modern value. By revising some of the observational parameters, he later made a more accurate estimate of the sun's mass which was within 32 percent of the modern value. In 1796 Laplace came within 1 percent of the 1976 accepted value which is 332,946 times the earth's mass.

By 1780, after a century of increasingly sophisticated attempts to determine the scale of the solar system, the astronomers had a fairly reliable set of figures. In fact, the solar distance of 24,000 earth radii and solar radius of 112 earth radii were within 10 percent of modern values. [6].

Johannes Fabricius published the first paper on sunspots in Germany during 1611 after observing it with a telescope. One year later Galileo Galilei (1564-1642) wrote a paper on sunspots arguing that the motion of sunspots proved the sun rotated.

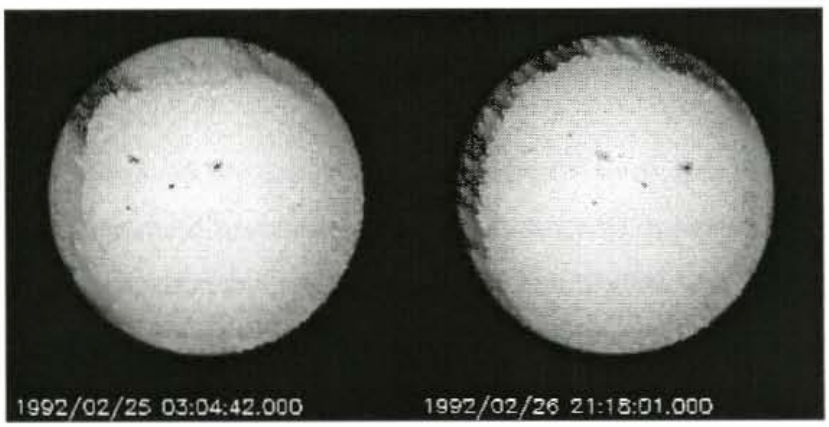


**Figure 1.1** Galileo used observations of the changing position of sunspots to prove that the sun rotated [13]

In 1826 Heinrich Schwabe (1789-1875) started a daily record of the number of sunspots and sunspot groups. As his data accumulated he observed a cyclic pattern in the number of sunspots. After observing two maxima and two minima of what appeared to be a 10-year cycle he sent a report of his discovery to an astronomical journal. This report was however passed over by most of his contemporaries, evidently he was too far outside the astronomical mainstream for his work to receive the attention it deserved. Soon after, his observation became significant when it was found that these sunspot variations were identical to magnetic variations. J. Rudolf Wolf (1816-93) then reviewed sunspot observations since Galileo's day and reported that the cycle's typical duration was in fact eleven years. He also reported correlation between sunspot cycles and magnetic variations.

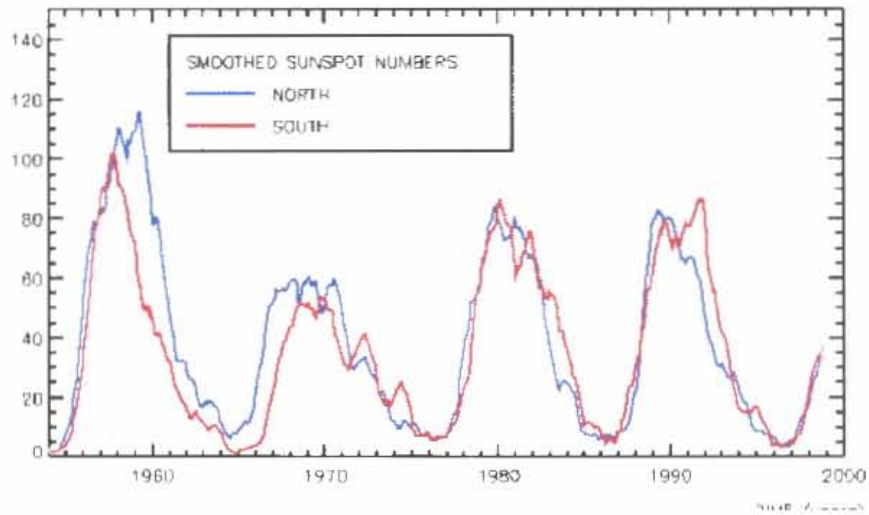


**Figure 1.2** Sunspot numbers through the last four cycle's [14].

These sunspot cycles are very significant since they are the directly related to the geomagnetic disturbances that induces currents in pipelines and cause havoc on power, communication and satellite systems. The next section describes the solar structure and dynamics.

## 1.2.2 The Solar Atmosphere And Solar Wind

The various components and thickness of the Sun's atmosphere are discussed in this section and depicted in fig. 1.3. The visible solar atmosphere consists of three regions with different physical properties. Optical photons originate in a thin layer of plasma, a region known as the photosphere. Within this region the temperature of the gas decreases from a value of 6500 K at the base to a minimum of 4400 K about 500 km higher up, at the top of the photosphere. Above this point the temperature begins to rise again.

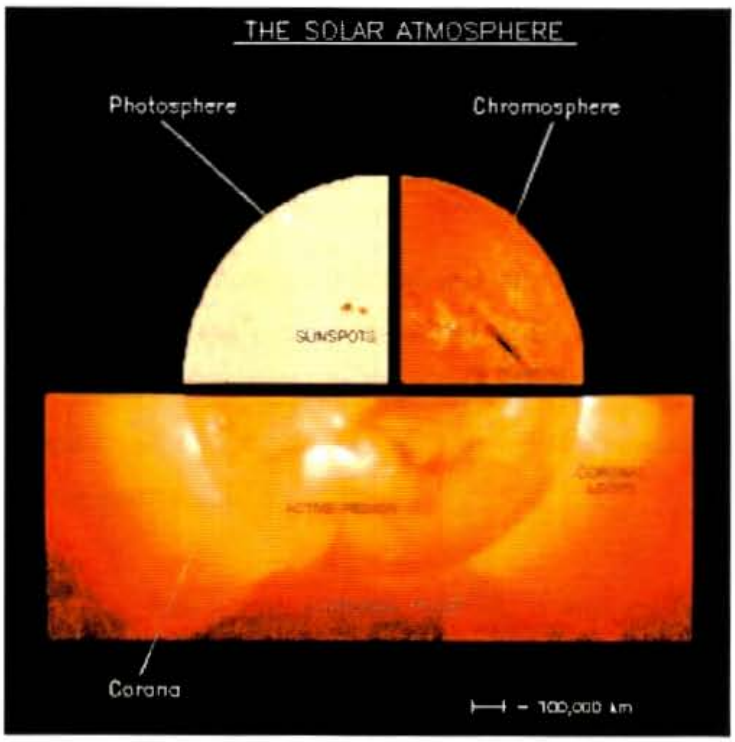


**Figure 1.3** The various components of the Sun's atmosphere [15].

Above this region lies the more transparent chromosphere with an intensity that is only about $10^{-4}$ of the value of the photosphere. It extends upwards for approximately 2000 km with the temperature increasing from 4400 K to about 25,000 K.

Corona extends from the top of a narrow transition region to the earth and beyond. In this transition region the temperature rises very rapidly reaching more than $10^6$ K before the temperature gradient flattens. During a total solar eclipse the radiation from the faint corona becomes visible as shown in fig. 1.4.

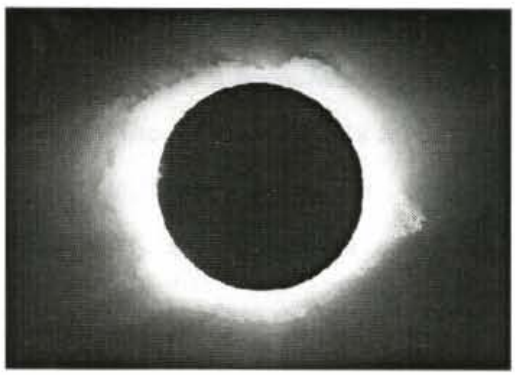

**Figure 1.4** Solar corona seen during a total solar eclipse (taken by Greg Babcock) [16]

The sun does not only emit the heat we can feel and light we can see but also various other radiations. These radiations control variations in the Earth's magnetic field and ionosphere and they include electromagnetic radiation, such as radio waves, ultraviolet radiation, X-rays and charged particle radiation consisting mainly of protons and electrons, known as the solar wind.

The magnetic field of the sun is not a perfect dipole, it appears to be squashed and confined to the equatorial plane due to a solar equatorial current sheet. The average position of the current sheet is tilted relative to the solar equator and contains folds. From X-ray images of the sun it can be seen that the X-ray emission is not uniform, but that dark regions called coronal holes exists. Coronal holes corresponds to those parts of the magnetic field were the magnetic field lines are open extending out to great distances from the sun. These holes source the solar wind, a continuos stream of ions and electrons following the magnetic lines out and away from the sun, moving through interplanetary space at a mean velocity of 300 to 400 km $s^{-1}$ [9]. Coronal holes occur mostly at the solar poles, which will not influence the earth lying in the sun's equatorial

plane. They do however move down towards this plane in a cyclic pattern and thus, similar to solar flares, increases the solar wind density and velocity.

By observing the tails of comets this ongoing mass loss from the sun can be seen. The latter are generally composed of two parts, a curved dust tail and a straight ion tail, both of which are always pointed away from the sun. The force exerted on the dust grains by radiation pressure is sufficient to push it back, while the electric force between the ions of the solar wind and the ions in the comet accounts for the direction of the ion tail. The aurora borealis and the aurora australis (the northern and southern lights, respectively) are also products of the solar wind, this phenomena is explained in the section 3.

### 1.2.3 The Solar Cycle

Quiet sun conditions are intermittently disrupted by a variety of transient features, some of which are illustrated in fig. 1.5.

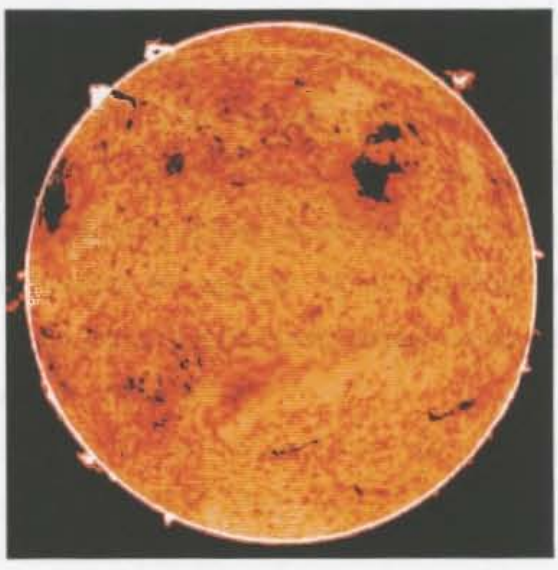

**Figure 1.5** A composite photograph of the sun showing several forms of activity (U.S. National Solar Observatory at Kitt Peak (Arizona) [30 APR 1999 15:37:34]) [17].

The surface of the photosphere is usually marked with dark spots of intense magnetic field, called sunspots. Their occurrence follows an 11-year cycle, going from minimum to maximum in about 4 years. Their formation can be explained with the aid of fig 1.6. At the beginning of the cycle, the lines of magnetic force run north and south between the Sun's magnetic poles. This is the period of minimum magnetic activity called the "Solar Minimum". As the Sun rotates, the Convection Zone spins faster at the equator than at the poles. Beneath the Convection Zone, the Radiation Zone spins as a solid mass. The different ways that these two zones move causes the Sun's magnetic field lines to be drawn out.

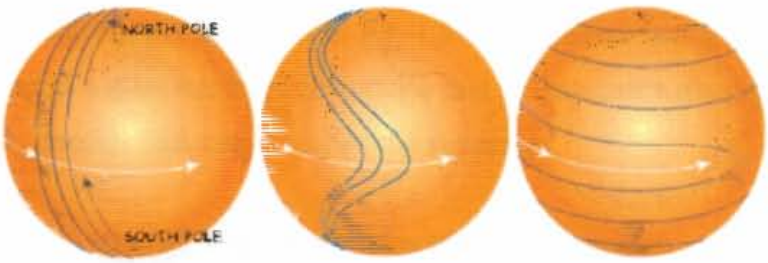


**Figure 1.6** Formation of sunspots [26]

Spot pairs in opposite hemispheres have opposite magnetic polarity and the same polarity as the nearer pole. The entire magnetic field of the sun reverses after such a cycle and therefore the sun is said to have a 22-year cycle. The initial spots at the beginning of a new sunspotcycle appear at relative high latitudes and as the cycle progresses, drift slowly towards the equator. Spots that form later in the cycle appear closer to the equator. This pattern is fairly symmetrical across the equator and forms the "butterfly pattern" as shown in fig. 1.7.

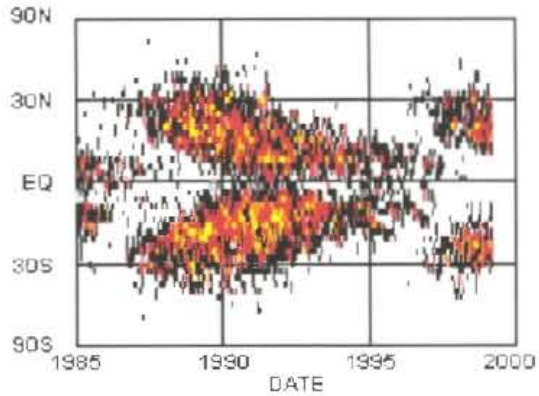


**Figure 1.7** The sunspot "butterfly pattern" [14].

Individual sunspots are short-lived features, typically not surviving more than one month or so [7]. A typical sunspot is shown in fig. 1.8. The darkest centre part is called the umbra that can have a diameter more than twice that of the earth's diameter. The umbra is surrounded by another dark region called the penumbra.

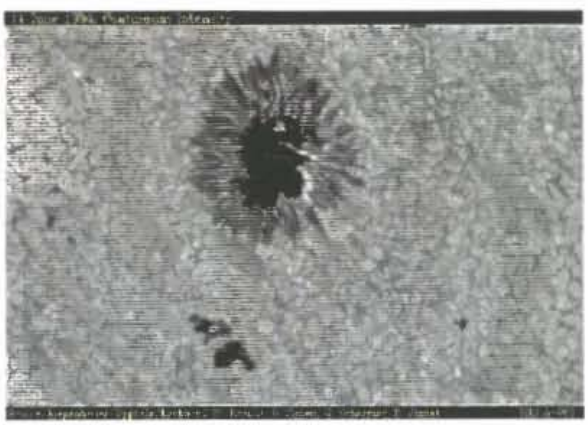

**Figure 1.8** A typical sunspot, showing the dark umbra and a penumbra [19].

Sunspots appear dark because they are cooler than the surrounding gas. The photosphere has a temperature of about 5500 degrees Celsius and a typical sunspot has a temperature about 3900 degrees Celsius. Their lifetime can be as short as an hour or two or as long as several months.

Solar flares are eruptive events occurring near sunspots. It's a brilliant region of intense emission and represents the violent instability of part of an active-region magnetic field and the resulting release of increased amounts of radiation and energetic particles. Flares have enormous dimensions with large flares reaching 100,000 km in length. Flares develop in regions of great magnetic intensity from which they draw their energy, namely sunspot groups, and the enhanced radiation due to them reaches the earth 8 minutes later [8]. Solar flares increase solar wind density and velocity, and when reaching the earth 12 to 48 hours later, the wind causes a sudden compression of the magnetic field, which is called a sudden impulse.

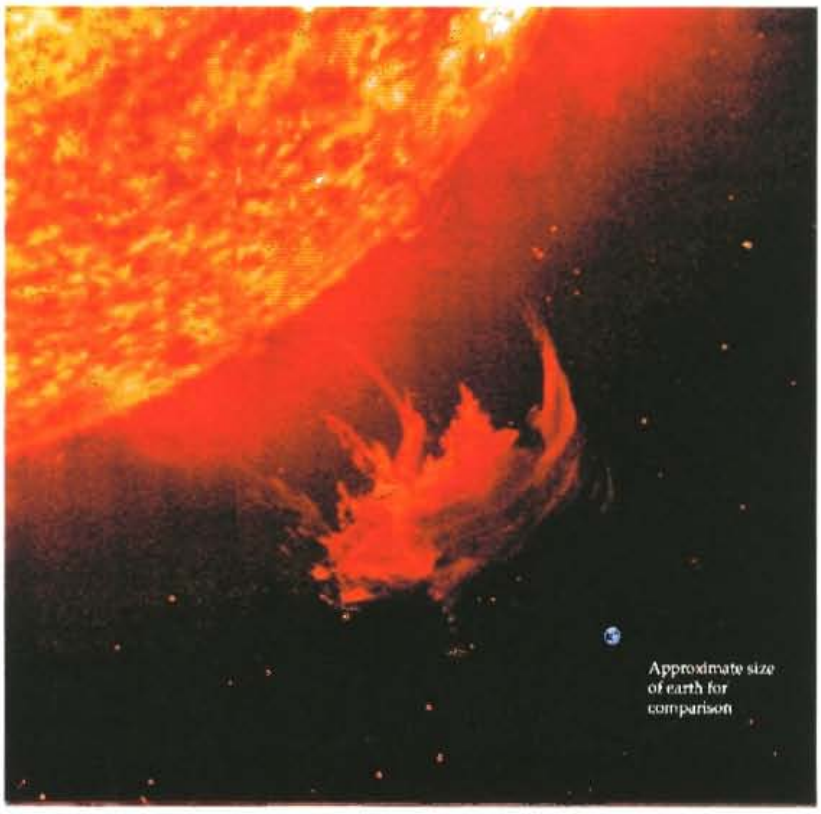


**Figure 1.9** A solar flare in comparison to the size of the earth [20].

Sometimes energetic particles and magnetic storms are observed at Earth without any exceptional flare activity preceding them, but they may be associated with a different solar phenomenon called "Coronal Mass Ejections" (CMEs). CMEs are huge bubble-shaped disturbances rising above active sunspot regions, expanding as they rise.

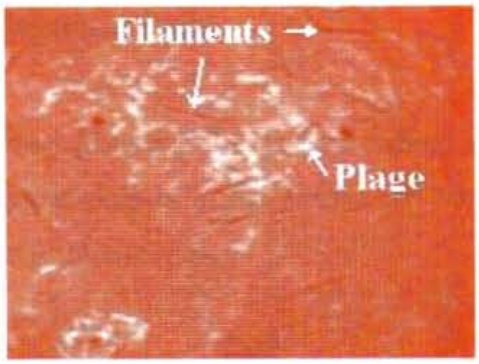


**Figure 1.11** Plages are due to moderate concentrations of magnetic flux [21].

A solar prominence is also related to the Sun's magnetic field. Quiescent prominences are curtains of ionised gas that reach well into the corona region. Prominences are made up of material that collected along the magnetic field lines of an active region, therefore the gas is cooler and less dense than that of the surrounding coronal gas. It will then "rain" back down into the chromosphere causing a spectacular sight.

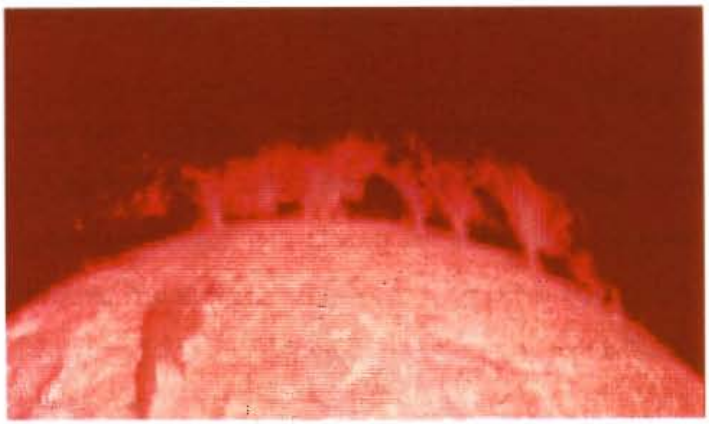

**Figure 1.12** Quiescent prominence [21].

## 1.3 The Earth's Magnetic Field

The earth has a rather strong planetary dipole field, which is roughly aligned with the spin axis (the north magnetic pole is in the Northwest Territories in Canada and the south magnetic pole in the Antarctic region).

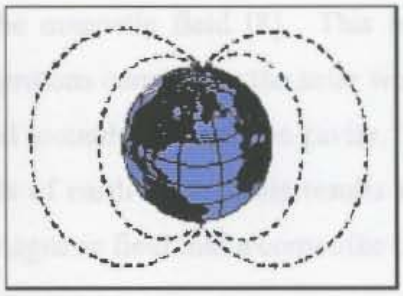

**Figure 1.13** The earth's dipole magnetic field [22].

The geomagnetic field is produced and maintained in the molten iron-nickel outer core by the self-exiting dynamo operation of the earth. The working principal is similar to that of a car's alternator. The rotating earth induces the current into the electrically conducting outer core, which creates the dipole magnetic field.

Emissions from the sun confines the Earth's magnetic field to region called the magnetosphere with its boundary called the magnetopause. This magnetic field protects the planet from incoming charged particles in the solar wind, as well as ionised cosmic rays. Instead of striking the surface some of the particles becomes trapped in the field were they bounce back and forth between the North and South Poles. These regions of trapped particles are known as the Van Allen radiation belts.

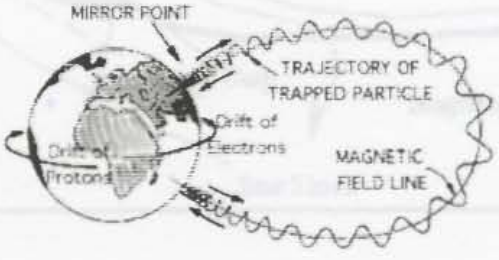


**Figure 1.14** Particles are trapped forming regions known as the Van Allen radiation belts [23].

## 1.4 Solar Wind Interaction with the Magnetosphere

The Earth's magnetic field carves out a cavity in the flow of hot plasma from the sun, or the so-called solar wind. It will push against the magnetosphere on the dayside with the magnetopause occurring roughly at about 10 earth radii were the plasma pressure of the solar wind is balanced by the magnetic field [8]. This is were the transition region occurs and the electrons and protons composing the solar wind can penetrate no closer to earth and are mostly deflected around the magnetic cavity. On the nightside the field is elongated extending hundreds of earth radii. This results from particle "friction" with the solar wind dragging the magnetic field into a cometlike tail.

The interplanetary magnetic field (due to the sun) has a component perpendicular to the ecliptic plane of the sun. Since the earth lies in this plane which contains many folds this component can vary between north or south in a couple of hours. When it points south it will merge with the Earth's magnetic field, which allows the plasma to enter through that region thereby "energising" the magnetosphere.

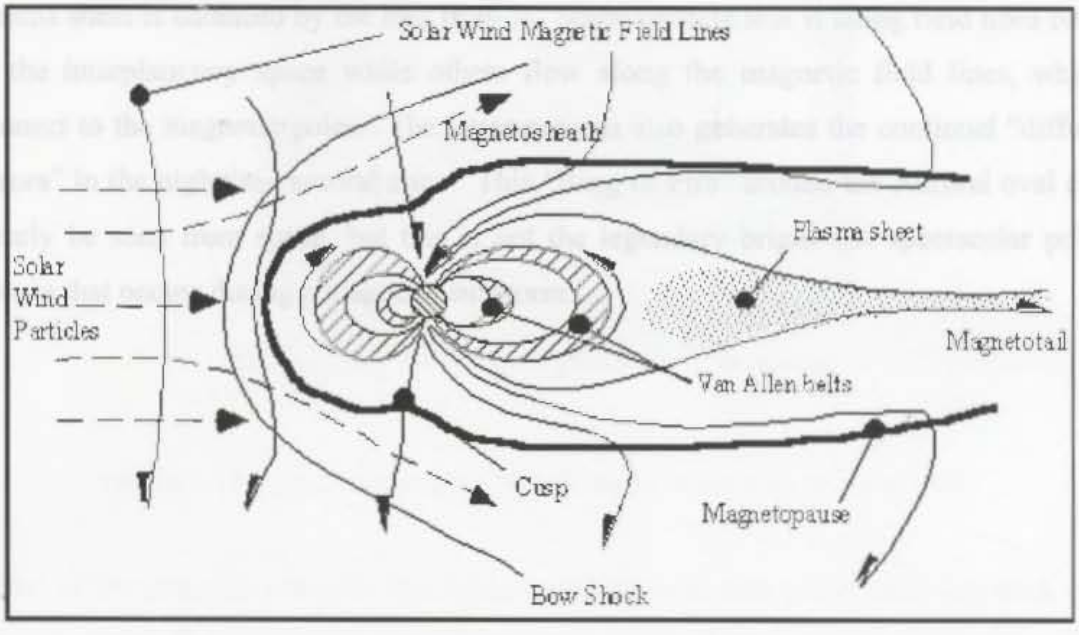


**Figure 1.15** Magnetospheric convention with a southward directed interplanetary magnetic field [24].

Another large fraction of the solar wind particles gain access at the front of the dayside magnetosphere by penetrating the bowshock, while the remainder are diverted around the magnetospheric cavity as illustrated in fig. 1.15.

The magnetic cusp region is where the Earth's magnetic field lines change from closed (joined to the other hemisphere) to open (swept into the magnetic tail). This forms a natural access funnel for some of the recently entered plasma into the Earth's dayside atmosphere, see fig 1.15. Dayside aurora is then formed as these particles collide with the oxygen and nitrogen of the upper atmosphere. The participating particles only have enough energy to penetrate down to height of about 250 km, hence they are red in colour since that's were the red spectral emission from atomic oxygen dominate.

The plasma that streams along the flanks of the magnetic tail forms the "mantle". The tail reconnects in the distance causing particles to accumulate in its central region and thus forming the plasma sheet. This is a stable situation as long as the build-up of the plasma sheet is balanced by the loss from it. Some particle loss is along field lines back to the interplanetary space while others flow along the magnetic field lines, which connect to the magnetic poles. The latter process also generates the continual "diffuse aurora" in the nighttime auroral zone. This "Ring of Fire" around the Auroral oval can clearly be seen from space, but this is not the legendary bright and spectacular polar corona that occurs during a magnetic substorm.

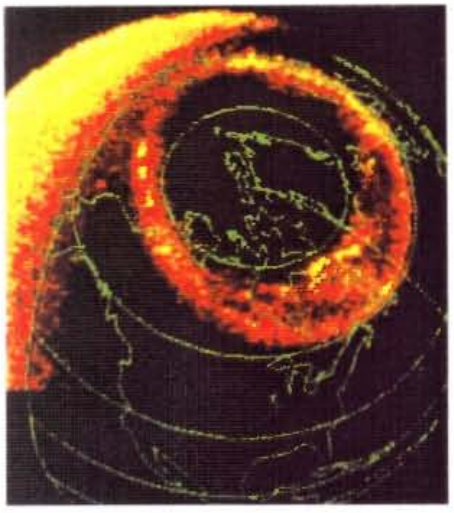

**Figure 1.16** Diffuse Aurora as seen from space (Picture taken by the Dynamics Explorer 1 Spacecraft) [28].

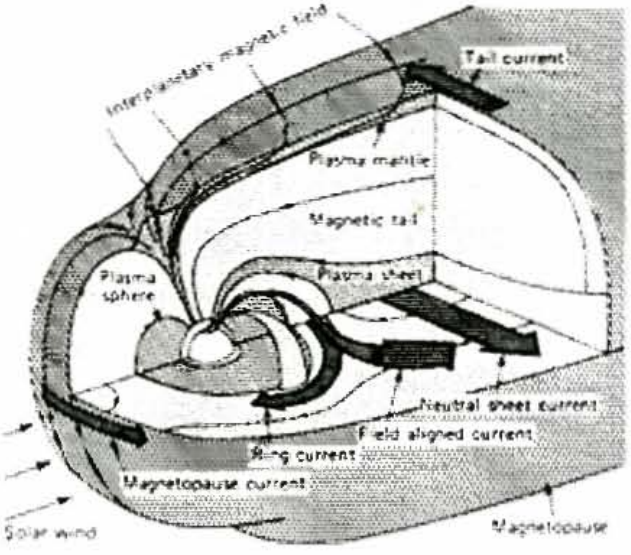


**Figure 1.17** Sketch showing the main features of the magnetosphere [25].

Some of the particles join the Van Allen radiation belts and while bouncing back and forth between the poles will drift around the earth, electrons eastward and protons westward. It occurs in the equatorial plane at distances of 3 to 7 earth radii above the

earth's surface [8]. This is called the ring current and significantly decreases the vertical component (H) of the earth's magnetic field over a period of hours.

The tail current divides the magnetopause into two lobes. It is the source of the stretched, parallel, magnetic field lines on the nightside. This current flows across the neutral plane at the equator, closing the circuit across the plasma sheet.

Magnetospheric substorms create the really bright and spectacular auroras, as well as disruptions on power and communication networks. It occurs when the sun is very active (large number of sunspots or coronal holes) and is the process were particles derived from the substorms and stored in the tail is released into the earth's atmosphere.

A magnetospheric substorm is explained with the aid of fig. 1.18. In the quiet state the plasma sheet thickness tapers of with increasing distance to the neutral point N. During a substorm the thinning of the plasma sheet occurs near to the centre of the tail (N') since the plasma sheet is unable to contain any further increases. The configuration is highly unstable and quickly relaxes to a more stable state during an explosive process that usually takes only 10 - 30 minutes. This process converts the accumulated magnetic energy into kinetic energy causing the particles in the plasma sheet to shoot away from the natural point (N') towards the earth.

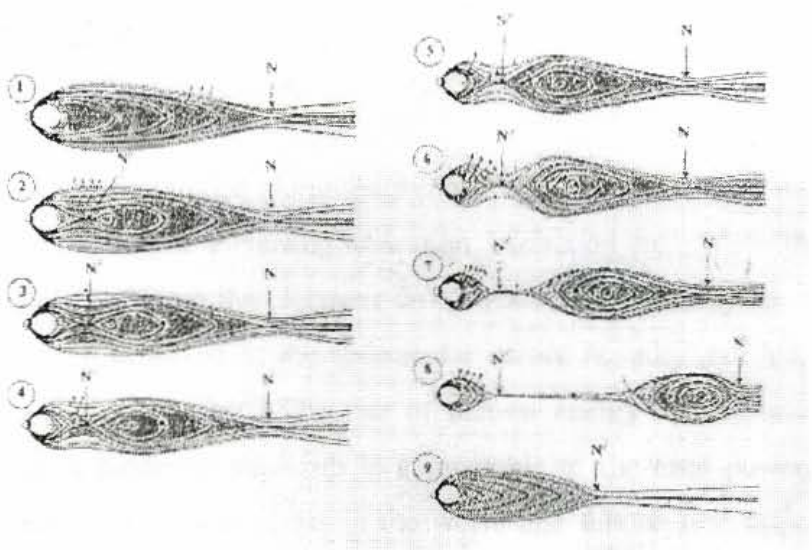

**Figure 1.18** Sequence of changes of magnetic field and plasma configuration during a substorm [8].

During a substorm the electrical particles is moved across the magnetic field lines and, similar to the process in the alternator of a car, an electric current will flow. This process will set up a large-scale convection motion toward the earth along the highly conductive field lines. The current can easily flow along the conductive strip in the auroral zone ionosphere. This gigantic current thus flows inward along magnetic field lines to the morning polar ionosphere, westward along the high conductivity strip in the ionosphere, and then along the magnetic field lines back to the equatorial plane as shown in fig 1.19.

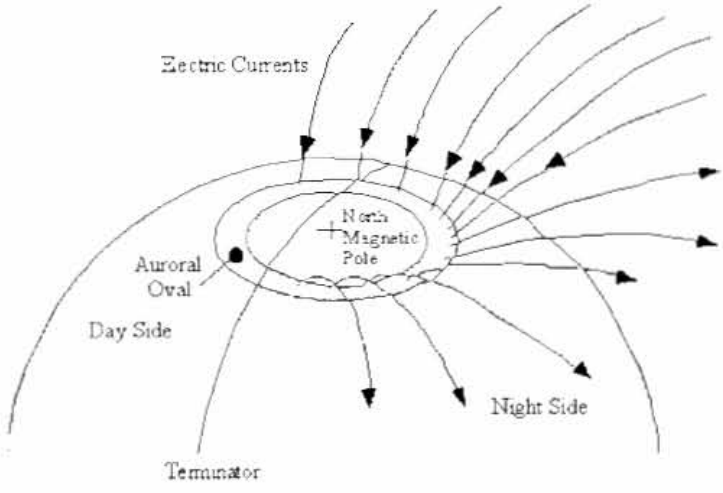


**Figure 1.19** Schematic of the northern half of the magnetospheric current system that flows during a substorm in the Auroral Oval [24].

The protons and electrons guided along magnetic field lines will collide with nitrogen and oxygen in high atmosphere causing ionisation, excitation etc. When the atoms or molecules recombine, or when the electrons drop back to lower energy levels, light are emitted which is then observed as the spectacular aurora borealis (northern lights) or aurora australis (southern lights). The rate of auroral energy release into the upper atmosphere during a moderate substorm is comparable to the total power-generating capacity of all man-made power plants in the world and this represents perhaps only 0.1% of the energy that precipitates the atmosphere [4].

**Figure 1.20** The spectacular Aurora Borealis (photographs by David Miller) [29].

A similar current wedge is formed in both hemispheres creating a remarkable similar auroral form under the same magnetic line [4]. The non-uniform auroral currents, or electrojets, follows general circular paths around the two magnetic poles at altitudes of 100 km or more and can have magnitudes of 1 million amperes. This can severely distort the earth's magnetic field; during the March 1989 disturbance compass needles was noticeable deflected [1].

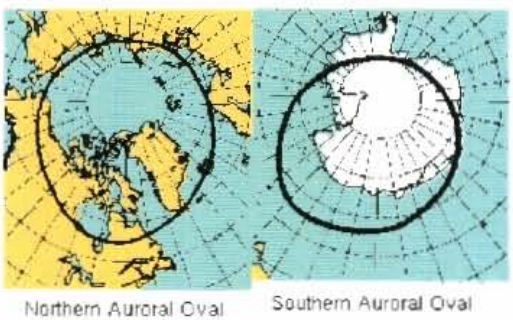


**Figure 1.21** The Northern and Southern Auroral Ovals [18].

Clearly, unlike we sometimes imagine, the earth is not just a small planet in the endless black void of empty space, but surrounded by a dynamically changing region of charged electrical particles and magnetic and electric fields.

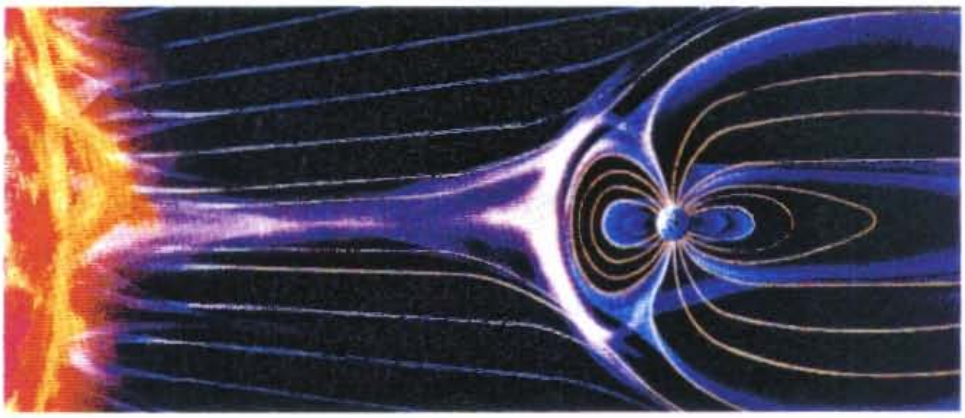

**Figure 1.22** The earth is surrounded by a dynamically changing region (Illustration by K. Endo. © Nikkei Science Inc.) [30].

## 1.6 Magnetic Field Measurements

The K index represents the deviation of the earth's magnetic field from normal at a specific geographic location. It serves as an indicator of the maximum variation of the magnetic field in a three-hour interval on the basis of a quasi-logarithmic scale (see table 1.1) with integer values from 0 (minimum activity) through 9 (super storm). Note that the amplitude ranges are unique to a particular station because of the latitude dependence of magnetic storms.

**Table 1.1** Limits of amplitude ranges (nT) for defining the K index at the Hermanus Magnetic Observatory [8].

| **K index** | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|---|
| **Range (nT)** | 3 | 6 | 12 | 24 | 42 | 72 | 120 | 198 | 300 | |

Magnetic storm conditions are considered to prevail when the degree of magnetic activity is taken to be a K-index of 5 or greater. It is considered a major storm when K=6 and a severe storm when K exceeds 6. The histogram in figure 1.24 indicates the number of major and severe geomagnetic storms over the past decade as measured at Hermanus. Note that the general trends and variations as measured at Hermanus are similar all over South Africa [8]. For reference purposes the K-indexes of the previous solar peak (1/01/89 – 31/12/92) can be found in appendix C.

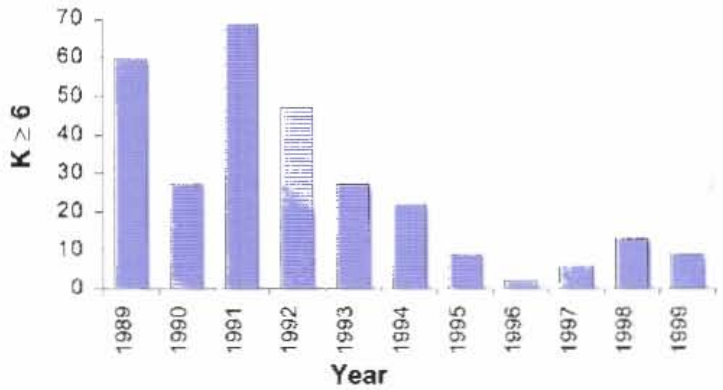


**Figure 1.24** Histogram indicating the number of occurrences of major and severe geomagnetic storms as measured at Hermanus since 1989.

The figure also illustrate the correlation with the previous sunspot peak (cycle 22) in 1991. Geomagnetic storms can take place at any time, however the probability of it occurring is higher during the occurrence of a large number of sunspots. Based on the statistics of previous cycles the next peak, that of cycle 23, is expected in the first quarter of 2000.

It is important to note that not so much the intensity but that the sustained rate of change of the magnetic field is an important factor [39, 40, 41]. Faraday's Law can explain this: the electric field is associated with the time derivative of the magnetic field, not with the variation amplitude. Fig 1.25 shows the rate of change of the magnetic field over 24 hours during a severe storm. This diagram also show how the K-index is not sufficient to determine the severity of the impact on the power system since the K-index of 9 after 9 hours was not at all similar in magnitude to the K-9 after 21 hours.

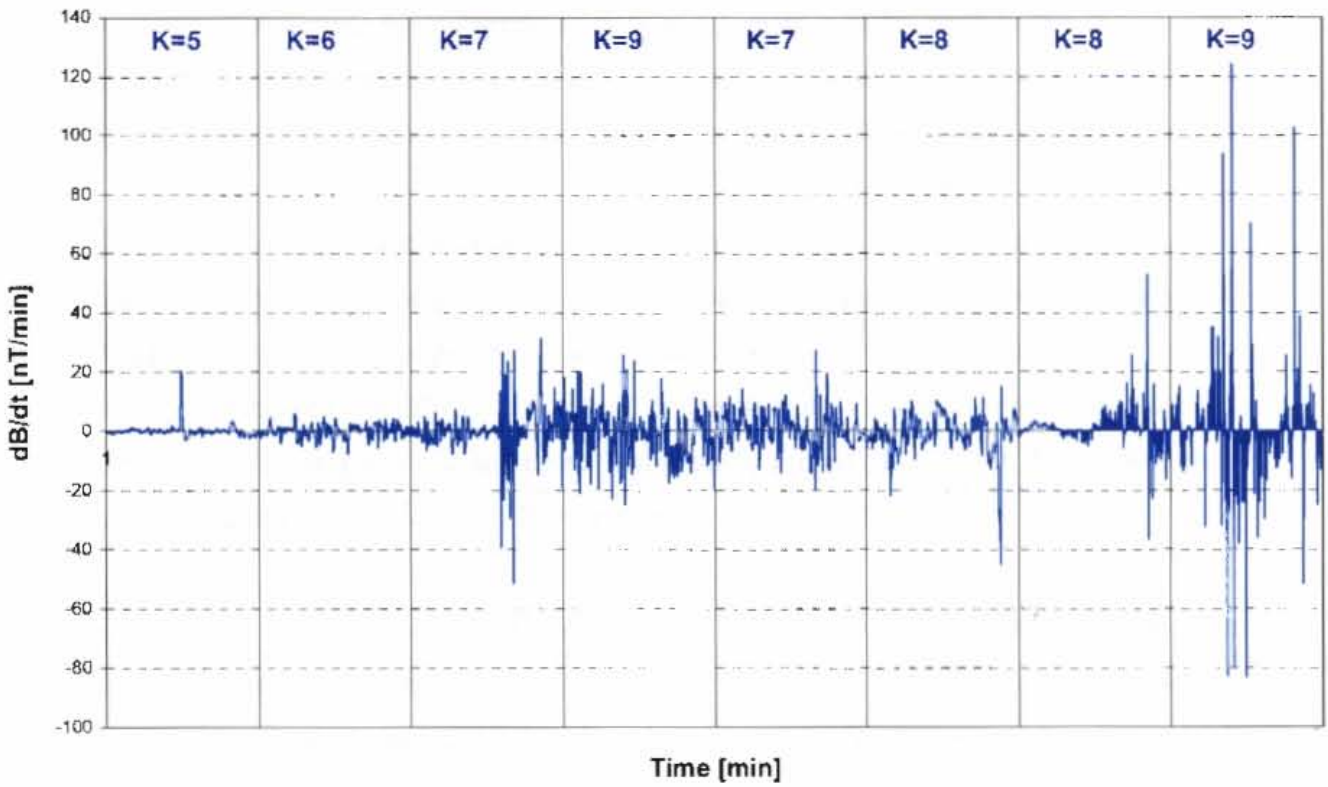


**Fig 1.25** The diagram illustrates the rate of change of the vertical component of the magnetic field as measured at the HMO during the severe storm on 13 March 1989.

# Chapter 2

# GIC Effects on Power Systems

## 2.1 INTRODUCTION

Power networks are more vulnerable today because of the increase in extent and interconnections, thus linking large cumulative earth surface potentials. Networks situated above igneous rock geology are most vulnerable since the relatively high resistance encourages more current to flow in alternative paths, such as the power lines located above these formations. Power systems adjacent to coastal areas are also more susceptible to GICs due to the large induced currents in the highly conductive seawater.

The GIC, having a fundamental period of approximately 5 to 15 minutes [34], are a quasi-dc, resulting in the simultaneous ac and dc excitation of energised transformers. Typical perturbations to power systems due to GICs include, fluctuations is system voltage, increased var flow, generation of harmonics, relaying problems, localised heating in transformers and increased audio noise output [1; 34]. In North America, voltage fluctuations in excess of 10% have been reported [78].

Countries at mid-latitude such as South Africa are located far from the magnetic pole and therefore do not experience the same severity of geomagnetic disturbances such as in Canada, North America or Scandinavia. However, long transmission lines, high resistance rock geology and coastal areas could present a risk during very severe storms.

This chapter will elaborate on the effect of GICs on power systems, with emphasis on the GIC induced half-cycle saturation of power transformers, the primary cause of perturbations on the power system.

## 2.2 Protective Relaying Effects

The high level of harmonic distortion caused by GICs may cause conventional protection systems to provide inadequate protection for capacitors, transformers and generators [80, 83]. The transformer differential relaying scheme has apparently been the most vulnerable to GICs [80]. Considers a star-delta transformer with GIC flowing on the star side; if the GIC cause saturation it will effectively reduce the magnetisation impedance which will result in a current unbalance in the relay circuit.

A risk associated with distance relays is that the saturation of a transformer can reduce the apparent impedance seen by the relay. If this apparent impedance is within the operating zone of the relay, an unnecessary tripping may occur [78, 80].

Another factor is the increased dependence of power systems on reactive power compensation such as shunt capacitors. These shunt capacitors are protected with neutral overcurrent relays. Harmonics caused due to transformer saturation will see these devices as a low impedance to ground and it may trip due to overcurrent. However, this should not be labelled a false trip since shunt capacitors need to be protected against overload due to harmonics.

Transformer neutral overcurrent relays need to filtered against harmonics since triplen harmonics may appear as zero sequence currents and provide a "false" overcurrent to the relay [2; 35]. Undervoltage relays can also misoperate due to depressed voltage conditions [80].

The effect of GICs on protection current transformers (CT) is of less concern. Since the core of these CT's are designed to handle large fault currents they are unlikely to saturate due to GIC. The only time a problem may occur is during the unlikely event that a fault occur at the same time as a GIC event. To date, no significant threat to reliable CT performance was found [2].

## 2.3 Saturation of Power Transformers and Reactors

A transformer core is made of high permeability ferromagnetic material. Its purpose is to provide a well-defined low reluctance path for magnetic flux. During normal operation, the majority of the flux will stay in the core. However, in the presence of GICs the core becomes saturated which lead to operation in the extremely non-linear portion of the core steel saturation curve (see fig.2.1). Excitation current is normally very small for large power transformers (less than 1% of rated load current) and they are designed to operate near the saturation point. These two characteristics will cause low values of GICs to push the core into saturation. Due to the quasi-dc nature of GICs, saturation will occur for one half of the ac cycle, hence the term half-cycle saturation, the root-cause of all power system problems that occur during geomagnetic storms.

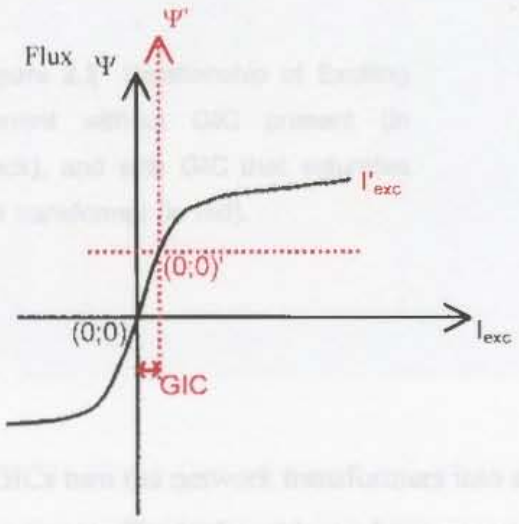


**Figure 2.1** Transformer magnetisation curve in the presence of GIC.

Under GIC bias the saturated core becomes a much higher reluctance path which requires more ampere-turns to produce the same amount of flux required. This will cause the transformer to draw an extremely large exciting current (see fig 2.2), rich in even and odd harmonics. The increased exciting current will cause a reactive power demand much greater than during normal operation for a single transformer. When a large number of transformers experience saturation due to GICs it will increase the reactive power demand significant when compared to either the total transformer demand or the total area connected load. VAR demands of this magnitude can cause severe bus and system voltage excursions.

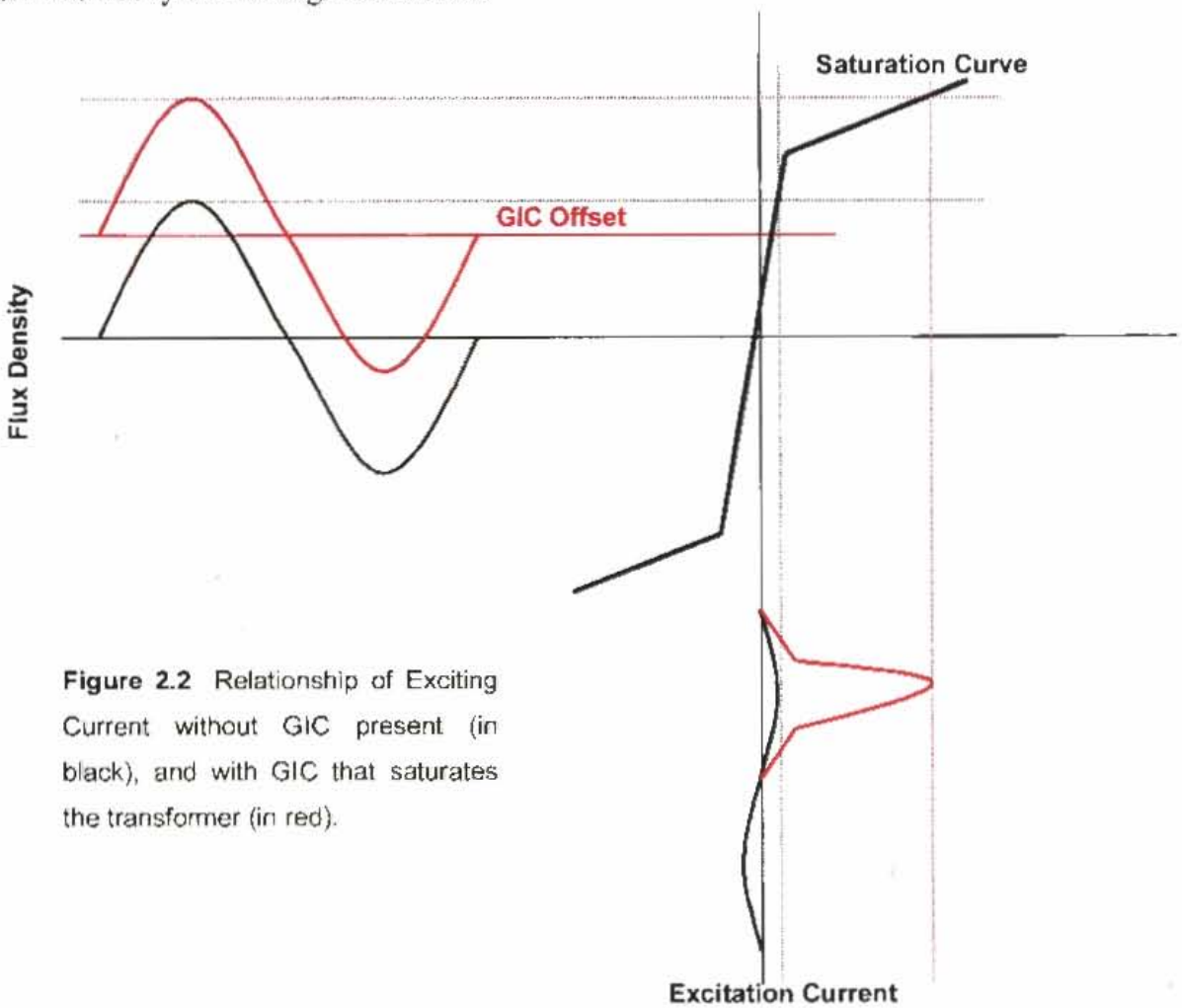


**Figure 2.2** Relationship of Exciting Current without GIC present (in black), and with GIC that saturates the transformer (in red).

In effect, GICs turn the network transformers into sinks of reactive power and sources of harmonic currents. Typical problems during a geomagnetic storm are unusual real and reactive power flows, voltage fluctuations, frequency shifts and undesired relay and

protective system operation [34]. GICs will increase generator output, decrease total system generation, increase transmission losses and reduce tie-line transfer capabilities.

## 2.4 Transformer Heating

The saturation of the magnetic core will also cause flux to exit the core steel for alternative paths, such as the tank wall, flux shields, clamps and other structural steel members of the transformer (see fig 2.2).

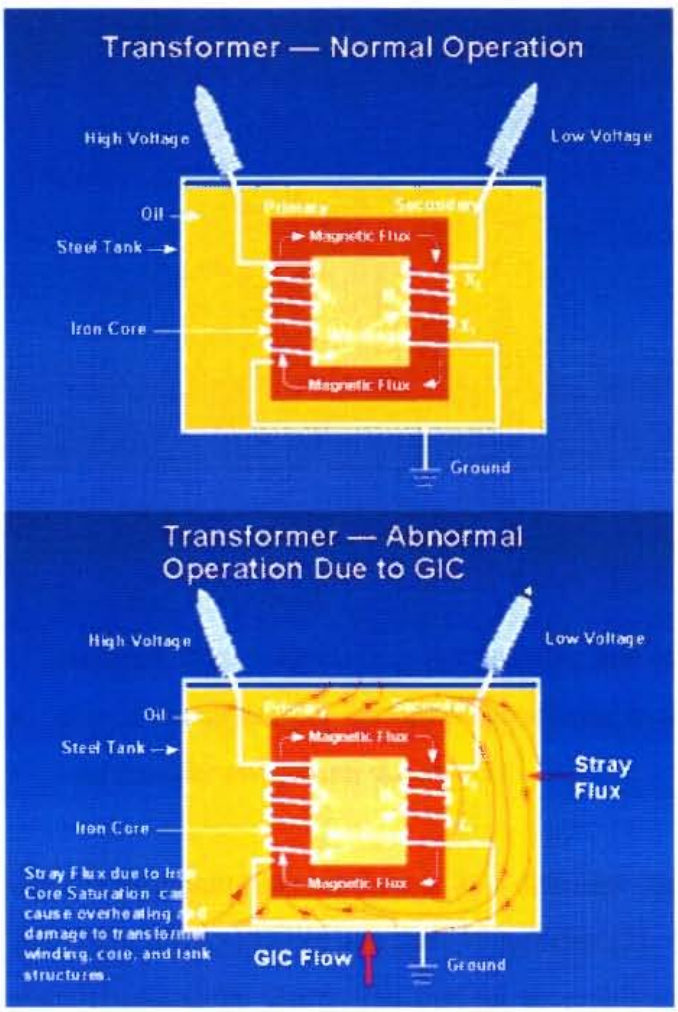


**Figure 2.3** GIC flow can severel disrupt the flux path in powe transformers [3]

The leakage flux due to core saturation will initiate eddy current heating in components linked by it and create hot spots. Hot spots can melt structural steel members and are likely to cause a cumulative damaging effect on the transformer winding insulation,

leading to premature transformer failure. An example of such damage occurred during the March 1989 storm to an 1200 MVA generator step-up (GSU) transformer at a nuclear plant in New Jersey which was damaged beyond repair (see fig. 2.3) [3]. At the same time the increased excitation current and higher harmonic content will add additional heating due to $i^2R$ losses.

**Figure 2.4** Damag caused to a transforme winding due to GIC [3]

Transformer heating due to stray flux is governed by the following factors [2, 35]:

- stray flux magnitude
- material characteristics (e.g. permeability and conductivity)
- size of the object (e.g. clamp) perpendicular to the stray flux
- heat transfer away from the object.

On a well-monitored transformer at a different site the temperature increased on a hot spot from 60° to 175° in less than 10 minutes [3]. This can lead to very severe damage since geomagnetic storms can last for several hours repeated over several days which will lead to the deterioration of insulation and subsequent decrease in life span of transformers and reactors. It was found that the failure rate of GSU transformers are 60% higher in the Northeastern US (the area of highest GIC susceptibility) than the rest of the US [3]. The same study showed that the failure pattern of these transformers

virtually mimics the cyclic pattern of the geomagnetic storm cycle with a time lag of approximately 3 years). GSU transformers of base load substations are most vulnerable since they are usually loaded to rated values and have limited margins to absorb additional heating stress [35].

## 2.5 Harmonic Generation in Transformers

The distorted excitation current drawn during transformer half-cycle saturation is full of both even and odd harmonics. This can cause misoperation of protective relays such as SVC overcurrent relays. This was the primary cause of the Hydro-Quebec blackout during the severe geomagnetic storm in March 1989. The harmonics generated caused 7 SVC's to trip on overload since their capacitive legs acted as sinks for it. Coincided with that the reactive power demand increased due to the half-cycle saturated transformers on the network. This led to severe voltage regulation problems, and ultimately to the collapse of the network [1].

The harmonic spectrum produced by transformers are generally unique to their construction type (five-leg core form, single phase units, etc.). The resulting current waveform of single-phase units will tend to be the same since they are subjected to the same waveform. However, transformers such as five leg core form or three phase shell form may produce very different waveforms since the individual phases will not experience the same saturation due to unbalanced magnetics [2].

The asymmetry caused by the dc offset in the transformer magnetisation lead to both odd and even harmonics. Normally utilities are well aware of odd harmonics in the power systems but few are prepared to handle the uncommon even harmonics. In general, the magnitude of harmonics decreases with an increase in the harmonic number and the magnitude of these harmonics increase almost linearly with an increase in the GIC magnitude [2].

## 2.6 The Expected Performance of Eskom Power Transformers

All single phase and three phase transformer designs are susceptible to GICs, and the saturation is determined by both the core configuration and the relative core leg dimensions [53]. The HV transformers most commonly used by Eskom are three phase, five limb autotransformers as well as a few single-phase units. Comparing the performance of all transformers the single-phase transformers are most affected by GICs since there are no opposing fields in the adjacent limbs [52, 53]. As far as three phase transformers are concerned the five legged type have showed to be the more susceptible to GICs by drawing more excitation current than the three legged core [52, 53]. Three-phase three-leg core-form transformers experience the least adverse effects to GICs since they offer no return path to the dc flux. This is since the GIC in the neutral will split evenly into the three phases, and since they are in phase will induce an opposing, equal flux [84].

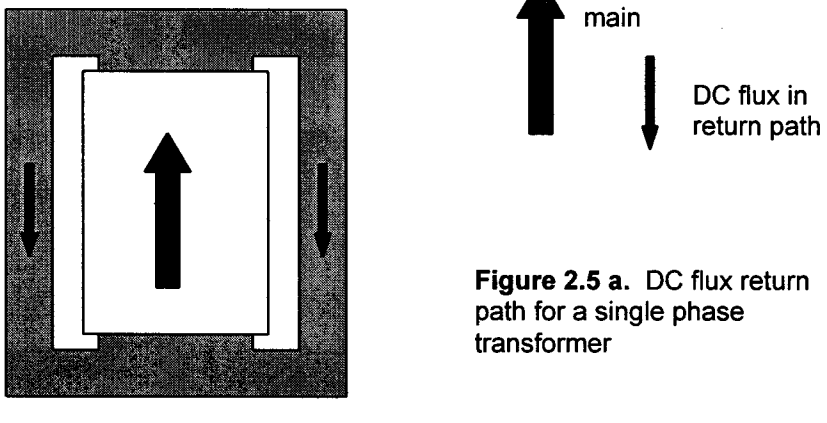


**Figure 2.5 a.** DC flux return path for a single phase transformer

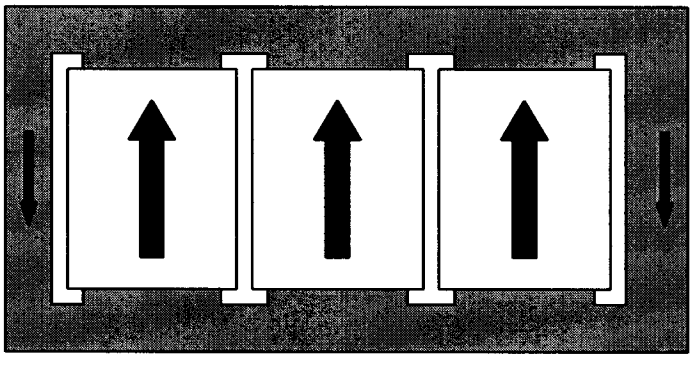

**Figure 2.5 b.** DC flux return path for a three phase, five limb transformer

Note that with autotransformers it is more difficult to make a theoretical prediction of the location of GICs in the power system since the current does not necessarily terminate at the earthing point. It can bypass the earthing point by flowing through the common winding to the next transformer. Therefore the GIC measured in the neutral of an autotransformer does not necessarily indicate its level of saturation since the measured value might only be a small fraction of the GIC in the series winding. The saturation of these transformers can be determined more accurately by rather monitoring the effects of GICs such as harmonics and reactive power flow.

# Chapter 3

# Historical Background

## 3.1 Introduction

Power networks are not the only technology affected by geomagnetic storms. In fact, the impact of these storms dates back from 1846 with reports of disruptions on the early telegraph systems [1]. Eventually, engineers and scientists were finding effects almost everywhere they looked. The first section of this chapter describes some of the disturbances to various technology systems during severe storms of the past. Section 3.2 is divided into two subsections and it's focussed on past incidents related to the effect on power systems. Its first subsection describes some of the events known to have occurred internationally due to GICs. The second subsection describes the results of an investigation into past incidents to equipment of the Eskom MTS that can be correlated with geomagnetic storms.

## 3.2 Disrupting Technology

The effect of geomagnetic storms was reported on the early telegraph system with reports dating back to 1859 when operators in Boston and Portland were able to disconnect their batteries and "for more than one hour held communication with the aid of celestial batteries alone" [63]. GICs has been so severe at times that at times it started fires at telegraph stations. It has also produced outages of phone cables as well as alternating sound levels on transatlantic cables.

Another technology greatly effected is that of pipelines. The greatest problem is the effect on the cathodic protection designed to prevent electrolytic corrosion at flaws in the pipeline coating. During a severe storm the pipe-to-soil potential vary rapidly making pipeline surveying almost impossible and exposing the pipeline to possible corrosion [39].

Following is a list of some of the effects during March 1989 when a number of massive solar flares occurred; causing some of the largest magnetic storms ever recorded (not including effects on power system, see following section) [8].

**Surface Technology Problems**

- South African geophysical exploration chief reported "conditions unlike any I've ever seen before; nothing worked."
- Mineral survey worker in Western Australia reported a totally disrupted survey, "never seen conditions quite like it."
- Pipeline surveying company in Australia could not understand their pipe-to-soil potential records and became concerned about probability of increased pipeline corrosion due to induced currents and potentials to ground.
- Power supply cables to undersea fibre-optic telecommunication cables monitored large voltage swings (500-600 V).

**Space Technology Problems**

- Stable low-altitude satellite began uncontrolled tumbling.
- GOES-7 high orbiting satellite had communications circuit anomaly on 12 March 1989, and lost imagery and communications on the next day.
- Aerospace engineer concerned over power panel problems.
- Japanese high orbiting communications satellite permanently lost half of its communications circuitry.
- Ageing low orbiting NASA satellite has dropped in altitude "as if it hit a brick wall". Dropping almost 5 km during the entire period.

**Ionosphere Communications Problems**

- March 6 - NBC warned affiliates of potential relay problems during the following two weeks.
- US Coast Guard reported many LORAN and HF-radio problems.
- US Navy MARS (10-20 MHz) circuits out world-wide but 144-148 MHz transceivers received signals from unusual long distances.
- Australia - many reports of poor HF-radio conditions on 13-14 March 1989. Polar to midlatitude circuits was useless and equatorial circuits very weak and noisy.

## 3.3 Disrupting Power Systems

Power networks are more vulnerable today because of the continual expansion and increase in interconnections, thus linking large cumulative earth surface potentials. Networks situated above igneous rock geology are most vulnerable since the relatively high resistance encourages more current to flow in alternative conductors such as the power lines located above these formations. Power systems adjacent to coastal areas are also more susceptible to GICs due to the large induced currents in the highly conductive seawater.

### 3.3.1 International Incidents Related to GICs

The Finnish Meteorological Institute (FMI) in collaboration with the Fingrid Power Company have monitored and studied GICs in the Finnish power system since 1977, i.e. for a longer time than the 11 year sunspot cycle. The largest GIC ever measured during this period occurred at Rauma on March 24, 1991. The one-minute mean value was 201A [36]. Also during this period the largest time derivative to be measured in southern Finland was 40nT/s, this occurred on July 13 to 14, 1982. Despite these large values, the Finnish power network has not experienced any significant disruptions due to GICs. This appears to be due to the transformer type and specific design being used.

They pay a lot of attention to leakage flux path to minimise the occurrence of hot spots and the transformers are generally only operated a half its rated value [51].

It is interesting to note that the Finnish neighbours, Sweden has not being as fortunate in escaping the detrimental effects of GICs. For instance, during the July 1982 storm mentioned above, they had 4 transformers and 15 lines tripped [36]. In fact, the first observations of GICs in Nordic countries was observed in Sweden, more than 70 years ago [44]. A comparison of the two networks (Sweden and Finland) has being done [44]. The main differences are listed in table 3.1.

**Table 3.1** The main differences between the Finish and Swedish power systems

| | **Finland** | **Sweden** |
|---|---|---|
| **Transformers** | Five limb, core type, full wound three phase transformers (400/400/125 MVA, 400/120/21 kV, Ynyn0d11). | 400/130 kV, and 400/220 kV three phase autotransformers. |
| **Earthing** | The 110 kV network is earthed through current limiting reactors. | The 130 kV system is solidly earthed due to the autotransformers. |
| **Reactive Power** | Compensation through reactors connected to the tertiaries of the system transformers | Compensation mainly through 400 kV shunt reactors connected to substation busbars. |

Note that previously the differential relays used in Sweden were not stable in the presence of harmonics, this has now been corrected [44].

It is interesting to note that GIC values are generally lower in North America than in Scandinavia, however their transformers are more sensitive to these currents which is evident from the number of problems they have had. One of their earliest disturbances occurred on 24 March 1940 [80]. In the northern United States and eastern Canada they had disturbances on 10 separate power systems, of which misoperation of transformer differential relays the most common problem. In 1957 saturation of power transformers saturated causing excessive harmonics and another storm in 1958 caused widespread voltage and power flow variations [80]. Also in 1958 the Bowater Power Company experienced outages on 4 generators. More differential relay maloperations was reported occurred in 1967, 1968 and 1970. A severe impact occurred in August 1972 which caused transformers to trip on differential relay, a capacitor bank on overcurrent, undervoltage breaker operation as well as unwanted supervisory operation [80].

To date, probably the most dramatic effect of GICs on power systems was the Hydro-Quebec collapse in Canada during a very severe storm in March 1989. The blackout affected more than 6 million customers. A total of 21 500 MW of load and generation was lost taking more than 9 hours to completely restore. Following is a description of the events that took place [1]:

The geomagnetic disturbance occurred early in the morning of 13 March 1989 causing GICs in the system. This caused excessive harmonics in the system which flowed into nearby static VAR compensators, whose capacitive legs is a low impedance to ground for the high frequency harmonics.

The harmonics overloaded the capacitors to such an extent that protective systems took the static VAR compensators off-line to prevent possible damage. Within a minute off storm onset, all seven static VAR compensators on the Hydro-Quebec 735 kV La Grande network tripped. This left the 9500 MW La Grande Hydroelectric complex without the support of voltage regulation and reactive power compensation. This, together with the increased reactive power demand by half-cycle saturated transformers contributed to voltage regulation problems.

About 8 seconds after the loss of the compensators, one of the five 735 kV La Grande lines tripped, almost immediately followed by the remaining 4 lines. This completely cut-off 9500 MW from the rest of the network. Frequency and voltage throughout the network fell. Automatic load shedding was not fast enough to restore a balance between load and generation available and in less than 30 seconds the entire network collapsed.

The same storm also cased unrepairable damage to a generation step-up (GSU) transformer in New Jersey. The 1200 MVA, 500 kV transformer overheated due to stray flux causing hot spots at certain concentrations. This kind of damage can be cumulative and a statistical analysis of GSU transformers in the U.S. showed that the failure rate was 60 percent more in GIC susceptible areas [3]. It is estimated that another storm of this magnitude could have a $3-6 billion loss in gross domestic product in the northeastern United States only [33].

A network seemingly even more sensitive to GICs is that of the UK. With a neutral dc current of only 5-25A, they have reported [85]:

- MVAr swings on generators
- Voltage changes ±5%
- Demand tripping by under voltage
- Generator negative sequence alarms
- Increased harmonic levels
- Bucholz trips / Transformer damage
- Communication channel failures

### 3.3.2 The Relation of Geomagnetic Storms and Network Equipment Failure in South Africa

The investigation into correlation between past system events and geomagnetic storms was conducted for the peak period of activity during the previous cycle, i.e. 1989 through 1994. The only available data was that of events concerning shunt capacitor banks, transformers and reactors. This data is unfortunately not sufficient to proof the possible existence or absence for that matter of GICs in the Eskom MTS. Data such as voltage change, generator MVAr swings, increased harmonic levels etc. will be essential to establish conclusive proof of the existence of GICs.

#### 3.3.2.1 Shunt Capacitors

No correlation between shunt capacitor trips and geomagnetic storms was found, which could be for numerous reasons such as network geometry, protection settings, magnitude of GICs, etc. It does not prove beyond doubt that there has not been any GIC related incidents at shunt capacitors on the network.

#### 3.3.2.2 Transformers and Reactors

The results of the investigation into transformer and reactor events that could be GIC related are shown in table 3.2. The table also lists all major to severe storms (K-index > 5)[1] which have occurred close to the date of an incident. See appendix C for all K-index data from 1989 through 1992.

[1] The K-index (a 1-digit number) is a 3 hourly indication of geomagnetic activity. See section 1.6 for a more thorough explanation.

**Table 3.2** Results of investigation between past system events and geomagnetic storms [86].

| Date | K-index sequence | Name | Description |
|---|---|---|---|
| 13 Mar 1989 | 5679 7889 | | |
| 14 Mar 1989 | 9765 3466 | | |
| 15 Mar 1989 | 6443 3332 | Poseidon-Neptune Reactor | Permanent fault on the reactor; interwinding fault |
| 28 July 1990 | 2456 6566 | Beta Reactor 4 | Internal fault; reactor was removed on 8/09/90 |
| 24 Mar 1991 | 2866 5378 | | |
| 25 Mar 1991 | 6643 4555 | | |
| 26 Mar 1991 | 6555 7443 | Hydra Transformer 21 | Permanent fault; reason unknown |
| 18 Apr 1991 | | Beta Reactor 4 | Neutral earthing reactor faulted |
| 18 Apr 1991 | | Beta Reactor 2 | Internal fault |
| 19 Jun 1991 | | Hydra Reactor 2[2] | Permanent fault, reactor was removed |
| 14 Aug 1991 | | Beta Reactor 4 | Neutral earthing reactor faulted and was disconnected |
| 19 Aug 1991 | 4375 4322 | Hydra Transformer 21 | Permanent transformer fault; transformer removed |
| 25/05/92 | | Hydra Transformer 3 | Transformer tripped on Buchholz protection |
| 06 May 1993 | | Hydra Reactor 1 | Reactor faulted internally. To be replaced. |
| 14 Dec 1993 | | Beta Alpha 2 Reactor | Red phase winding faulted. |
| 21 Mar 1994 | | Hydra Poseidon 1 Reactor | Reactor faulty and replaced |

[2] This followed a period of very severe storms from 4/06/91 – 17/06/91 (see appendix C).

These incidents provide circumstantial evidence tat GICs might exist in the Eskom MTS. From this data it appears that the Hydra and Beta substations may be susceptible to GICs. It is also interesting to note that the Poseidon-Neptune reactor that failed was commissioned less than one year before it failed and was removed [87]. Unfortunately the only investigation report available for the above incidents is the failure of the two 765 kV shunt reactors at Beta. An extract from this report by Eskom Transmission Group is available in appendix D. The observations made at Rotek correspond exactly to the damage that would be caused by GICs. The following quotes highlight some of these observations:

> *"3.3 The upper shunts controlling the leakage flux from the winding returning to the yokes showed signs of overheating. The shunt insulation had also deteriorated.*
> *3.4 At the tips of three upper magnetic shunts on the line side, a number of laminations had spread open and bent towards the yoke. They had penetrated the insulation causing electrical contact. The yoke laminations had melted at these points.*
> *3.5 Molten metal particles from the yoke laminations were found between some of the winding conductors."*
>
> *"The shunts collecting the stray flux from the winding situated at the top neutral end of the winding overheated due to high flux density."*

The estimated costs only for repairs at Beta alone was R 4 892 000 in 1991.

Note that it is rarely the case that transformer or reactor failure occurs at the exact same time as a geomagnetic storm [84]. Normally the overheating or hot spots will cause insulation breakdown, which will effectively decrease the expected life span of the equipment. At times the overheating may become so severe that part of the magnetic circuit, such as the leakage flux shunts, may melt and short out windings below as in the case of the Beta reactors.

# Chapter 4

# Modelling and Predicting GICs

## 4.1 Introduction

The theoretical evaluation of GICs in power networks can be divided into two parts:

- Network calculation: to calculate the GICs produced by this electric field in the different parts of the system. This is done by using Ohm and Kirchhoff's laws as well as Thevenin's theorem
- Geophysical calculation: to calculate the earth surface potential (ESP) from Maxwell's equations.

By combining these two steps the GIC at every substation can then be calculated. This chapter will address these two steps and describe how they are combined to predict the GIC at different substations during a geomagnetic storm.

## 4.2 Network Calculation

### 4.2.1 Model Description

Figure 4.1 illustrates how the ESP caused by geomagnetic fluctuations will cause the GIC to flow into the power system. After entering the transformer through the neutral, it will split equally among the three phases of the transformer into the transmission line. From there it will terminate at the star point of the next transformer. In the case of an autotransformer, this current does not need to terminate at the earth point, and may flow via the series winding to the next transformer.

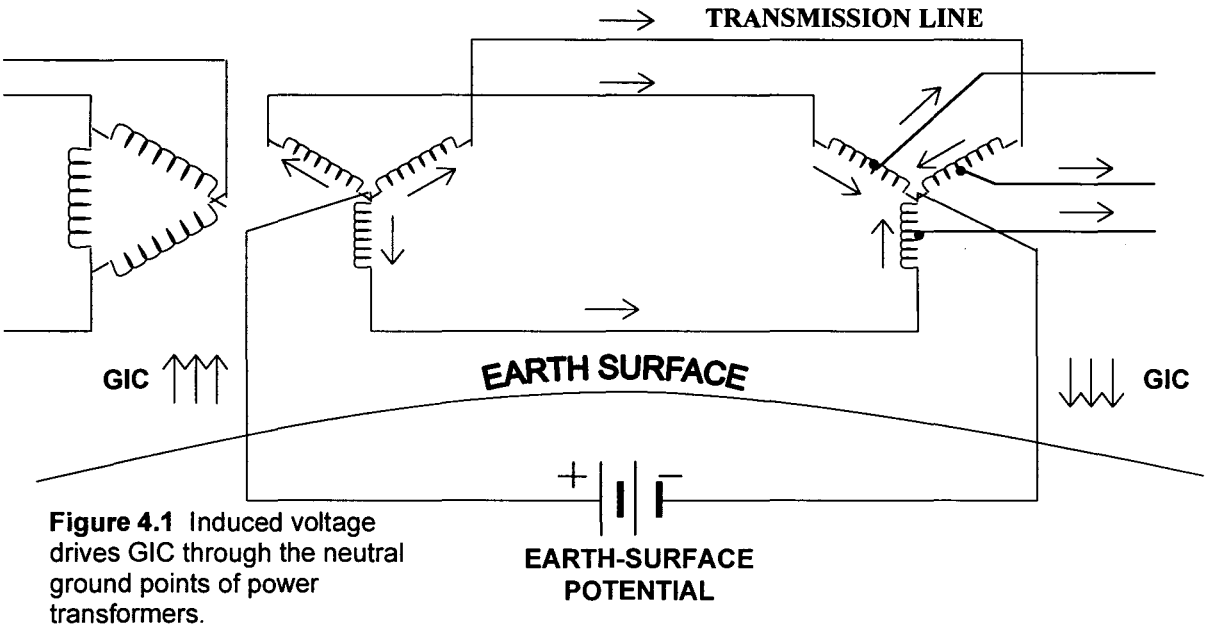


**Figure 4.1** Induced voltage drives GIC through the neutral ground points of power transformers.

Since it is quasi-dc current, network equipment and transmission lines will be represented by only their dc-resistances and the three phases are considered to be in parallel. The source is represented by an idealised voltage source and exists between the grounded neutrals or ground mats (see fig. 4.2b) with a finite resistance to remote earth. Since an accurate value of this resistance is not available for all substations, it can be assumed to be 0.1Ω at the coast and 0.5Ω inland [43, 44, and 49]. Transformers are represented by their winding resistance values in parallel as shown in figure 4.2.

Symbols used in figure 4.2 are:

$R_L$ = line resistance per phase.

$R_Y$ = resistance of grounded star-connected winding per phase.

$R_S$ = autotransformer series winding resistance per phase.

$R_C$ = autotransformer common winding resistance per phase.

$R_{gi}$ = grounding resistance of bus i.

$I_{ni}$ = neutral GIC at bus i.

$V_{espi}$ = earth surface potential at bus i.

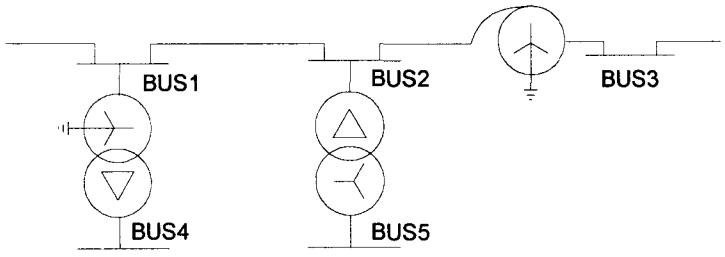


**Figure 4.2a** Sample network to illustrate modelling procedure

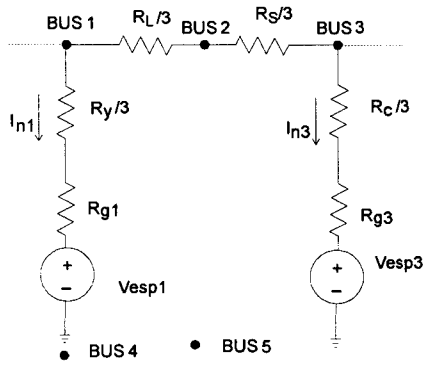


**Figure 4.2b** DC model of sample network

At some sites there is more than one transformer in parallel (as well as shunt reactors) which will correspondingly change the value of the transformer resistance.

The ac resistance of overhead transmission lines is normally reduced by 5% (skin effect factor) to give dc resistance. The effect of shield wires can be neglected since their high resistance as well as tower footing resistance limits currents through it, also since the concern lies with the GICs in the phase lines [47, 50].

### 4.2.2 Network Configuration

The following procedure to calculate the contribution of the network configuration to determine GICs has been derived by Lehtinen & Pirjola [42]. Note that bold letters will be used to represent vectors.

The earthing points of the network are defined by $p_1,\ldots,$ pm (fig. 4.3). All these points have earthing resistances $R_1 \ldots R_m$, which are the sum of the dc resistance of the transformer and the resistance of the transformer earth to true earth. Each pair of points ($p_i$, $p_j$) is interconnected by a transmission line with resistance $R_{ij}$. This value will be infinite should a pair of points not be connected. Current flowing in between nodal point $p_i$ and $p_j$ is denoted Ii and the earthing current at a node $p_j$ is denoted by $I_j$ with the positive direction into earth.

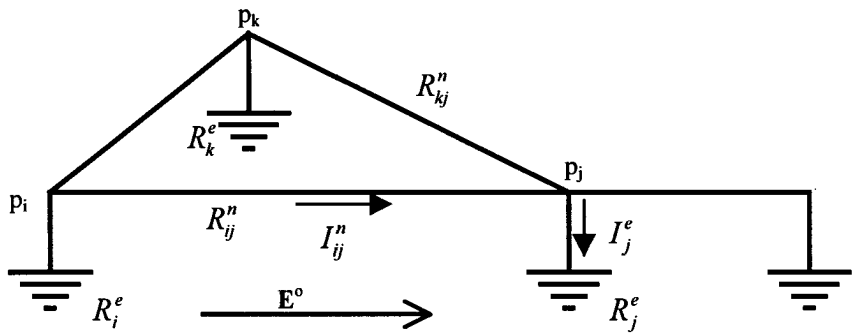


**Figure 4.3** Definition of symbols used for a transmission network

The earthing resistance is described by the earthing impedance matrix **Z**. Since no time dependence exists for the quasi-dc GIC, all the elements of the matrix will be real. The earthing point is assumed to be far enough from each another so that the earthing current at one point does not affect the potential at another point. This assumption will imply that the earthing impedance matrix is simply a diagonal matrix with diagonal elements equal to the earthing resistances $R_i$. The values of these elements are the sums of the resistances of the transformers, with all three phases in parallel, and the actual earthing resistances.

The electric field at the earth's surface without the conductor network is denoted $\mathbf{E}^o(\mathbf{r}, t)$ and is called the open-circuit electric field. Let sij denote the path of the line between a pair of nodal points $p_i$ and $p_j$. The open-circuit electromotive force between these points can thus be defined as the path integral of the open-circuit electric field $E^o$ along the path $s_{ij}$:

$$V_{ij}^{o} = \int_{sij} \mathbf{E}^{o} \cdot dl \qquad (4.1)$$

When the conducting circuit is included in the calculation it will introduce two fields $\mathbf{E}^{cur}$ and $\mathbf{E}^{ind}$. The latter is due to time variations of the currents in the conductors. The former arises due to the flow of GIC current in the earthing resistance $R_j$ and line resistance $R_{ij}$. Therefore, the closed circuit field $\mathbf{E}^e$ and corresponding electromotive force can be found as follow:

$$\mathbf{E}^{e} = \mathbf{E}^{o} + \mathbf{E}^{cur} + \mathbf{E}^{ind} \qquad (4.2)$$

and

$$V_{ij} = V_{ij}^{o} + V_{ij}^{cur} + V_{ij}^{ind} \qquad (4.3)$$

Once again, because of the quasi-dc nature of GICs, $\mathbf{E}^{ind}$ and thus $V_{ij}^{ind}$ can be ignored. For the same reason the field $E^{cur}$ has a single-valued potential, $U_j^{cur}$ wit respect to true earth and can be calculated as follow:

$$U_j^{cur} = \sum_{i=1}^{m} Z_{ji}^{e} I_i^{e} \text{ , or as a matrix equation} \qquad (4.4)$$

$$\mathbf{U}^{cur} = \mathbf{Z}^{e}\mathbf{I}^{e} \qquad (4.5)$$

From Kirchoff's voltage law the potential inside the loop between a pair of point pi and pj will be (see fig 4.4)

$$V_{ij}^{o} - (U_j^{cur} - U_i^{cur}) - I_{ij}^{n} R_{ij}^{n} = 0 \qquad (4.6)$$

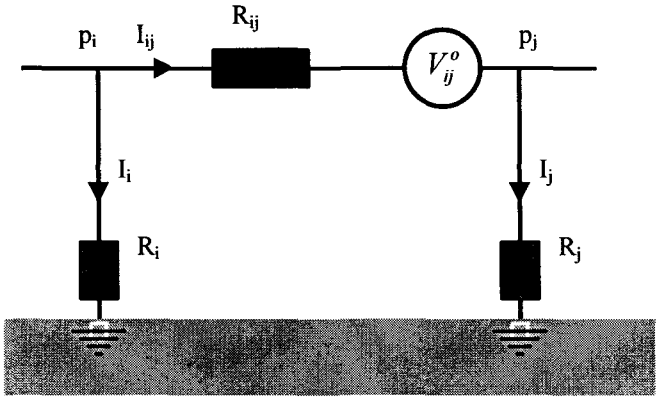


**Figure 4.4** The closed loop between two nodal points $p_i$ and $p_j$

And from Kirchoff's current law the currents at the nodal points will be defined by

$$I_i^e = \sum_{j \neq i} I_{ji}^n = -\sum_{j \neq i} I_{ij}^n \qquad (4.7)$$

Solving for $I_{ij}$ from equation (4.6) and substituting into (4.7) yields

$$I_i^e = -\sum_{j \neq i} (V_{ij}^o + U_i^{cur} - U_j^{cur}) / R_{ij}^n \qquad (4.8)$$

which can also be written as

$$I_i^e = -\sum_{j \neq i} \frac{V_{ij}^o}{R_{ij}^n} - U_i^{cur} \sum_{j \neq i} \frac{1}{R_{ij}^n} + \sum_{j \neq i} \frac{U_j^{cur}}{R_{ij}^n} \qquad (4.9)$$

The network admittance matrix is defined as

$$Y_{ij}^n = \begin{cases} -1/R_{ij}^n, i \neq j \\ \sum_{k \neq i} 1/R_{ik}^n, i = j \end{cases} \qquad (4.10)$$

Once again because of the assumed time independence of GICs, the elements of the matrix are purely real.

Equation (4.9) can then be simplified to

$$I_i^e = -\sum_{j \neq i} \frac{V_{ij}^o}{R_{ij}^n} - U_i^{cur} Y_{ii}^n - \sum_{j \neq i} Y_{ij}^n U_j^{cur} \qquad \text{and thus,}$$

$$I_i^e = -\sum_{j \neq i} \frac{V_{ij}^o}{R_{ij}^n} - \sum_{j} Y_{ij}^n U_j^{cur} \qquad (4.11)$$

A column vector $\mathbf{J}^e$ is defined by

$$J_i^e = \sum_{j \neq i} J_{ji}^n \qquad (4.12)$$

where

$$J_{ij}^n = V_{ij}^o / R_{ij}^n \qquad (4.13)$$

Therefore equation (4.11) can be written as

$$I_i^e = \sum_{j \neq i} J_{ji}^n - \sum_{j} Y_{ij}^n U_j^{cur} \qquad (4.14)$$

and thus

$$I_i^e = J_i^e - (\mathbf{Y}^n \mathbf{U}^{cur})_i \qquad (4.15)$$

which from equation (4.5) can be written as

$$I_i^e = J_i^e - (\mathbf{Y}^n \mathbf{Z}^e \mathbf{I}^e)_i \qquad (4.16)$$

Equation (4.16) can be expressed as a complete matrix equation

$$\mathbf{I}^e = \mathbf{J}^e - \mathbf{Y}^n \mathbf{Z}^e \mathbf{I}^e \qquad (4.17)$$

and therefore to calculate the earthing currents

$$\mathbf{I}^e = (\mathbf{1} + \mathbf{Y}^n \mathbf{Z}^e)^{-1} \mathbf{J}^e \qquad (4.18)$$

where Y is the network admittance matrix and Z the earthing impedance matrix. The elements of this column vector $\mathbf{I}^e$ depend only on the resistance and structure of the power system. They are therefore not the GIC value at the nodal points but a representation of the network and called "Network Constants".

These network constants must be calculated respectively for an eastern and northern electric field of 1V/km, i.e. by changing the elements of column matrix $\mathbf{J}^e$. If the electric field is known the constants are used to calculate the GIC as follow:

$$I_{GIC} = aE_x + bE_y \qquad (4.19)$$

where "a" is the GIC for the eastward surface potential of 1V/km and "b" the GIC for a northern surface potential of 1V/km. These surface potentials of 1V/km are constant and independent of the geology. The actual or theoretical electric field is represented by $E_x$ and $E_y$ which will determine the magnitude of the GIC at the site. $E_x$ represents the electric field in the northern direction and $E_y$ the eastern electric field.

Section 4.2 will elaborate on the calculation of the electric field and section 4.3 will show by means of an example how these calculations are applied.

## 4.3 Geophysical Calculation

Countries located at high latitudes beneath the auroral zone will generally use a three dimensional model to calculate local earth surface potentials (ESP). The ionospheric current is assumed to be one million amperes, about 600 km long, 450 km thick, and located at about 120 km above the earth surface [35]. This detail is not necessary for countries at mid-latitude such as South Africa where it is sufficient to assume an infinite current sheet with a spatially constant current density [50, 66]. The primary field is thus a vertically propagating plane wave.

The model for regional geology depends on the conductivity, permeability and permittivity of the area considered. A uniform earth model can be assumed when using the plane wave method.

The procedure to calculate the electric field has been derived by Viljanen and Pirjola [68]. The earth is described as a half-space with a constant conductivity of σ and the geomagnetic field propagates as a vertical plane wave in the earth. Using Cartesian co-ordinates, the x-axis is directed to the magnetic north, y to the magnetic east and z downwards. The electric field is then obtained by

$$E(T_N) = \frac{2}{\sqrt{\pi \mu_0 \sigma \Delta}} \left( R_{N-1} - R_N - \sqrt{M}\, b_{N-M} \right) \qquad (4.20)$$

where Δ is the sampling interval, N is the sample number, M = 10 [66] and

$$R_N = \sum_{n=N-M+1}^{N} b_n \sqrt{N-n+1} \qquad (4.21)$$

where bn = Bn – Bn-1 (B being the magnetic component).

Since magnetic and electric fields are perpendicular, $E_x$ will be calculated from $B_y$ and $E_y$ from $B_x$. A simplified example has been included in appendix E to illustrate step by step how the electric field will be calculated from equations 4.20 and 4.21 in section 4.2.1.

## 4.4 Example Of Calculating GICs

The following example will illustrate how GIC can be calculated at various substations of an interconnected transmission network. The model will consist of six 400 kV substations numbered 1 through 6 as shown in fig 4.5.

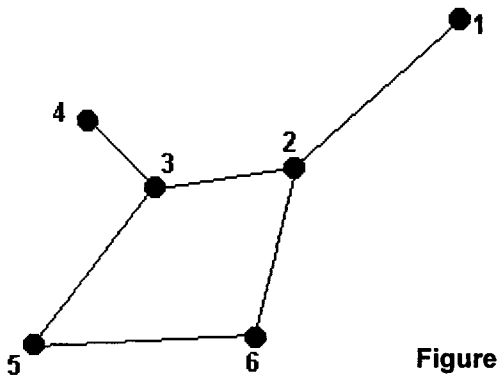


**Figure 4.5** Single line diagram of model

### 4.4.1 Network Constants

The line data necessary to calculate the admittance matrix (equation 4.10) is shown in the table below.

**Table 4.1** Line resistances between any pair of connected substations (see comments at end of table)

| Station Numbers | | No. of lines | Voltage | Line length | Line type | $R_{pu}$/km | Line resistance |
|---|---|---|---|---|---|---|---|
| i | j | | [kV] | [km] | | | $R_{ij}^{n}$ [Ω] |
| 1 | 2 | 2 | 400 | 320 | Twin Dinosaur | 0.000015 | 1.280 |
| 2 | 3 | 2 | 400 | 125 | Twin Dinosaur | 0.000015 | 0.500 |
| 2 | 6 | 1 | 400 | 215 | Quad Wolf | 0.000030 | 3.440 |
| 3 | 4 | 1 | 400 | 105 | Quad Wolf | 0.000030 | 1.680 |
| 3 | 5 | 2 | 400 | 257 | Twin Dinosaur | 0.000015 | 1.028 |
| 5 | 6 | 1 | 400 | 262 | Quad Wolf | 0.000030 | 4.192 |

**Comments**: To determine the actual line resistance $R_{ij}^{n}$, the following formula is used:

$$R_{act} = R_{pu}*(V_{line})/(S_{base})$$

where $R_{pu} = (R_{pu}/km)*(\text{line length})$, $V_{line}$ = 400 kV and, $S_{base}$ = 100 MVA

This value must then be divided by three to take into account that it is a three-phase conductor. That value must again be divided by the number of three phase lines in parallel (assuming parallel conductors are of the same type and length).

From table 4.1 and equation (4.10) the admittance matrix can be calculated:

$\mathbf{Y}^n =$

| | | | | | |
|---|---|---|---|---|---|
| 0.781 | -0.781 | 0 | 0 | 0 | 0 |
| -0.781 | 3.072 | -2.000 | 0 | 0 | -0.291 |
| 0 | -2.000 | 3.568 | -0.595 | -0.973 | 0 |
| 0 | 0 | -0.595 | 0.595 | 0 | 0 |
| 0 | 0 | -0.973 | 0 | 1.212 | -0.239 |
| 0 | -0.291 | 0 | 0 | -0.239 | 0.530 |

As mentioned in section 4.1.2 the earthing impedance matrix is a diagonal matrix with real elements. These values are the sum of the resistances of the transformers with all three phases in parallel, and the actual earthing resistances. As mentioned in section 4.1.1 the latter is generally assumed to be 0.1Ω at the coast and 0.5Ω inland [43, 44, and 49]. For the model the transformer and reactor resistances will be assumed to be equal for all substations with a value of 0.3 Ω ($\frac{0.9}{3}\Omega$ = 0.3 Ω). If there are more than one transformer or reactor at a site in parallel the value have to be changed correspondingly. However, this has been shown to be insignificant at times since, depending on the model, the line resistances are dominating and therefore changing the earthing resistance had almost no effect on the calculated value [43]. The necessary data to calculate the earthing impedance matrix is shown in table 4.2.

**Table 4.2** Data necessary to calculate the earthing impedance matrix. The diagonal elements of the $\mathbf{Z}^e$ are those shown in the last column.

| Substation No | Actual earthing resistance [Ω] | No of transformers at substation | No of reactors at substation | Calculated earthing resistance $R_i^e$ [Ω] |
|---|---|---|---|---|
| 1 | 0.1 | 2 | 1 | 0.13 |
| 2 | 0.5 | 2 | 0 | 0.40 |
| 3 | 0.5 | 2 | 0 | 0.40 |
| 4 | 0.5 | 2 | 0 | 0.40 |
| 5 | 0.1 | 2 | 1 | 0.13 |
| 6 | 0.1 | 1 | 0 | 0.40 |

The final values to be calculated are those of the column matrix $\mathbf{J}^e$ (see equation 4.12 & 4.13). This matrix must be calculated twice, once for an eastern and once for a northern electric field of 1V/km. The following table lists these values.

**Table 4.3** Calculating the column vector $\mathbf{J}^e$. For calculating the horizontal and vertical distances, substation 1 was used as a reference point. As mentioned in section 4.1.2, positive direction is assumed to be into earth, therefore the values for substations to the east and north are assumed negative and visa versa.

| Substation No | Connected to | Line resistance [Ω] | Horizontal surface potential [V] | Vertical surface potential [V] | $J^n_{ij}$ Horizontal | $J^n_{ij}$ Vertical |
|---|---|---|---|---|---|---|
| 1 | 2 | 1.280 | 250 | 175 | 195.31 | 136.72 |
| 2 | 1 | 1.280 | -250 | -175 | 79.22 | -28.58 |
| | 3 | 0.500 | 130 | 25 | | |
| | 6 | 3.440 | 50 | 200 | | |
| 3 | 2 | 0.500 | -130 | -25 | -41.06 | 108.84 |
| | 4 | 1.680 | 90 | -60 | | |
| | 5 | 1.028 | 170 | 200 | | |
| 4 | 3 | 1.680 | -90 | 60 | -53.57 | 35.71 |
| 5 | 3 | 1.028 | -170 | -200 | -225.01 | -200.52 |
| | 6 | 4.192 | -250 | -25 | | |
| 6 | 2 | 3.440 | -50 | -200 | 45.10 | -52.18 |
| | 5 | 4.192 | 250 | 25 | | |

Combining these values through equation (4.18) the network constants (or GIC values for a constant field of 1 V/km) can be determined: $\mathbf{I}^e = (\mathbf{1} + \mathbf{Y}^n\mathbf{Z}^e)^{-1}\mathbf{J}^e$

**Table 4.4** The network constant value "a" is the value for an eastward surface potential of 1V/km and "b" that for a northern surface potential of 1V/km.

| Substation No | a | b |
|---|---|---|
| 1 | 126 | 188 |
| 2 | 5 | 39 |
| 3 | 42 | -19 |
| 4 | 37 | -47 |
| 5 | -163 | -198 |
| 6 | -47 | 36 |

Once the actual electric field is known the GIC can be calculated for each substation individually, from equation (4.19): $I_{GIC} = aE_x + bE_y$. The electric field will be calculated in the next section.

### 4.4.2 Magnetic Data and GIC

An example of the results during a very severe storm is given in figure 4.6 where the predicted GIC at substation 5 of the model is compared to the magnetic field (X and Y), as well as the magnetic field variation (dX/dt and dY/dt). The magnetic data used for the graph were sampled over a 120 second interval for a period of 180 minutes during a very severe storm (K = 9). The detailed magnetic data and corresponding electric field is available in appendix F.

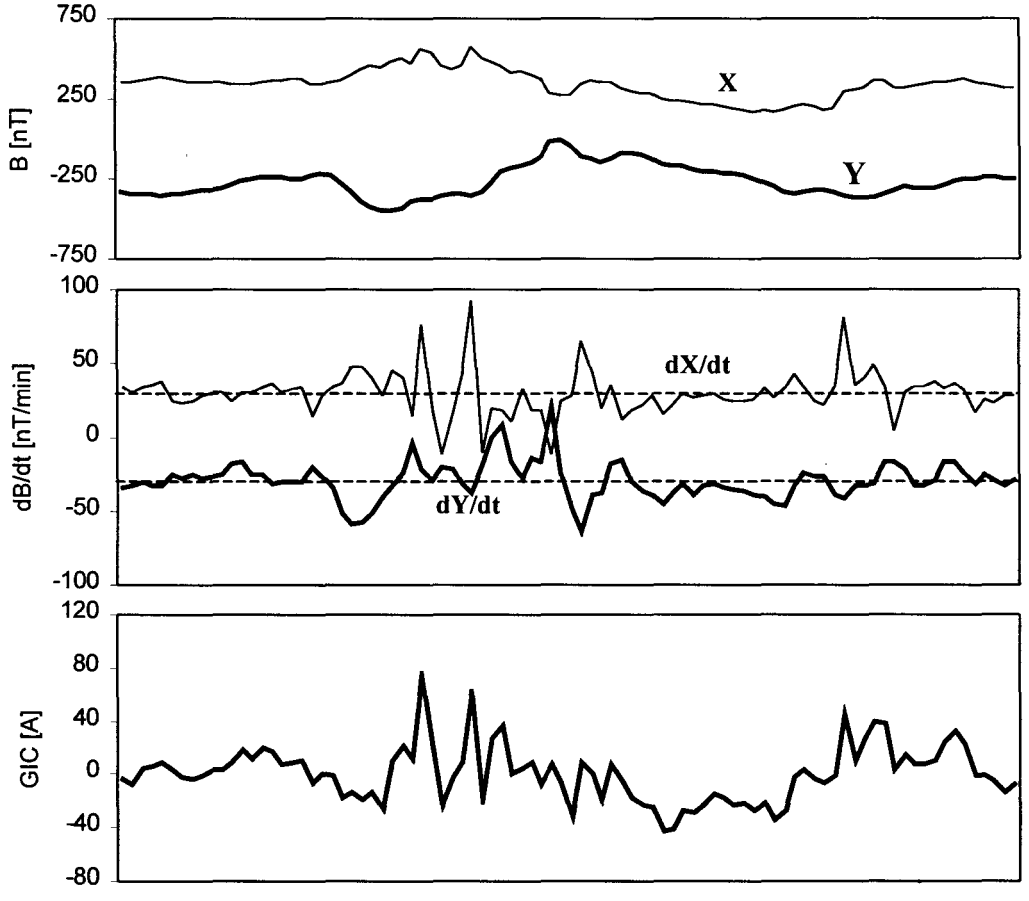


**Figure 4.6** Top panel: X (thin line) and Y (thick line) at substation 5 during very severe storm of 13 March 1989. Note that X is normalised around 9500 nT and Y around –4000 nT.

Middle panel: dX/dt (thin line) and dY/dt (thick line). Zero levels are plotted with dashed lines.

Bottom panel: Predicted GICs at substation 5. Positive current flows into the earth.

### 4.4.3 Interpretation of Results

From table 4.4 it is evident that the most susceptible substations are 1 and 5. The main reason for this is the fact that they are at the ends of the longest effective span of the network. Distance plays a major role since the earth surface potential will increase linearly with the distance between the nodes. Another contributing factor is the fact that both these substations have very little earthing resistance (see table 4.2), however this will not dominate the GIC value since the line resistance is higher and therefore of more significance. In fact, it was shown that on some networks the value of the earthing resistances have almost no effect [43].

Table 4.6 shows how different values of the earthing resistance influence the GIC. From the table it is evident that substations 1 and 5 will be the most susceptible even when all substations are allocated the same earthing resistance value. Combined with the fact that the magnitude does not change drastically it shows that the line length and also the fact that GICs have to terminate at these end points play a more significant role than the earthing resistance.

**Table 4.6** The influence of earthing resistance value on the GIC

| | $R^e_{1,5} = 0.13\Omega$ $R^e_{2,3,4,6} = 0.40\Omega$ | | $R^e_5 = 0.13\Omega$ $R^e_{1,2,3,4,6} = 0.40\Omega$ | | $R^e_1 = 0.13\Omega$ $R^e_{2,3,4,5,6} = 0.40\Omega$ | | **All substations**: $R^e_i = 0.40\Omega$ | |
|---|---|---|---|---|---|---|---|---|
| **Substation No** | a | b | a | b | a | b | a | b |
| **1** | 126 | 188 | 108 | 162 | 124 | 186 | 107 | 160 |
| **2** | 5 | 39 | 16 | 55 | 0 | 32 | 10 | 48 |
| **3** | 42 | -19 | 45 | -13 | 27 | -37 | 31 | -31 |
| **4** | 37 | -47 | 38 | -46 | 34 | -50 | 35 | -49 |
| **5** | -163 | -198 | -162 | -196 | -131 | -159 | -130 | -158 |
| **6** | -47 | 36 | -46 | 38 | -53 | 28 | -52 | 29 |

This table also shows that substation 4 is least affected by changing the earthing resistance at 1 and 5. This is since is substation 4 is remote from the mesh network and therefore not significantly influenced by the "line" of current between 1 and 5 (see fig 4.5). The line connecting 3 to 4 is also much higher than that connecting 3 to 5.

It was also found that changing the value of the earthing resistance at substation 6 had almost no influence on its GIC magnitude. This is since the lines connecting it with 2 and 5 has very high resistance compared to the earthing resistance at 6 and are therefore dominant on the GIC magnitude.

Figure 4.6 comparing the predicted GIC at substation 5 to the magnetic field (X and Y), as well as the magnetic field variation (dX/dt and dY/dt) shows clearly that the GIC is more dependant on the rate of change of the magnetic field rather than its magnitude. This is as expected since from Faraday's law it is known that the magnitude of the electric field is related to the rate of change of the magnetic field. There is no simple relation between the GIC and dB/dt but it is without doubt more related than the GIC with B.

# Chapter 5

# Measurements and Mitigation

## 5.1 Introduction

GIC interaction with a power system is a non-linear phenomenon (due to the presence of the magnetic core) and requires direct measurement to accurately determine its magnitude and effects. Parameters of importance will be the variation of the magnetic field, the magnitude of the GIC in the transformer neutral and the level of the saturation caused by it. The latter will be evident through measurements such as harmonic distortion, reactive power demand, transformer noise and transformer heating. Section 5.1 will elaborate more on the measurements as proposed here.

Through mitigation the detrimental effects of GICs can be limited and even avoided. Both passive and active devices have been developed for this purpose. Another popular alternative is through system operations i.e., changing the network during the event of a storm to reduce GICs. These methods will be discussed in section 5.2.

## 5.2 Measurements

There are three main methods to monitor GICs [2]:

- Measure perturbations of the earth's magnetic field in terms of its variation with time dB/dt
- Measure the GIC in the transformer neutrals or transmission lines
- Measure the adverse effects on the network such as transformer saturation; this is done through parameters such as harmonic distortion, reactive power demand etc.

Magnetic data such as dB/dt and values of the K-index is available from magnetic observatories. Once such an institution in South Africa is that of the CSIR in Hermanus. If this data is available on a real time basis it can be used to warn network controllers of a magnetic storm to which they can react and effectively minimise the GIC. This will be discussed in section 5.2.

The GIC is usually measured in the transformer neutral since it is easier and more practical compared to installing a dc transformer on a transmission line. The problems with the latter are that dc transformers for transmission line voltages are quite limited and it is more difficult to install. A method adopted in Finland to measure GICs in the transmission lines was by using a magnetometer near a 400 kV line in Porvoo [36]. This can be done in very isolated areas since this instrument is very sensitive to other disturbances.

The half-cycle saturation of the transformer not only depends on the GIC in the neutral but also on its load which will push it beyond the knee-point of the saturation curve. Monitoring methods that can indicate this level are the following:

- Harmonic distortion
- Reactive power demand
- Noise level of transformer
- Heating of transformer

The EPRI SUNBURST program is a global monitoring network used by participating utilities. Its purpose is to provide a database for multiple sites regarding the effects of similar disturbances on different network configurations as well as various transformer types and designs. The harmonic components measured by this system are those of the second to the eight. The reactive power demand at a site can also be calculated from this system since it measure the current and voltage on each side and determines the phase angle relationship. The increase in reactive power demand of the system instead of individual equipment can also be measured at various generators and reactive power compensators who will attempt to provide this extra demand.

Transformer noise will occur because the ferromagnetic material changes size slightly when magnetised causing the vibration of the lamella of the core. This level increases drastically during half-cycle saturation due to the increased magnetisation and presence of harmonics. This indicates undesired mechanical strain of the transformer and will also be a psychological problem in power transformers operate near human activity [54].

Transformer heating takes place when the leakage flux from the saturated core causes hot spots. This heating can be quite dramatic and cause the failure of transformers such as the GSU transformer (as mentioned in section 3.2.1) that was damaged beyond repair. Another well-monitored transformer had a rapid rise in internal heating due to GIC when the temperature of a hot spot on the tank increased from 60°C to over 175°C in as few as 10 minutes.

Since measuring equipment is very expensive to buy, install and maintain it should only be installed at sites most susceptible. These sites can be identified through the modelling of the network. Generally the sampling interval to measure GICs are 10 s with an average value determined every minute [36].

## 5.3 Mitigation

### 5.3.1 Passive Devices

Due to the quasi-dc nature of GICs devices such as Transmission Line Series Capacitors can block their flow. Although such devices will provide additional line impedance compensation and increase the power flow transfer limit, they are not feasible for the sole purpose of blocking GICs. Very low impedance capacitors make this method more cost effective. These devices offer almost no compensation, and hence have very little voltage across them [35].

Another method that is under investigation is the installation of a series capacitor in the transformer neutral. This device has a by-pass circuit in parallel with it for the purpose of shunting fault currents. This method might however interfere with the safe operation of the ac system [62].

### 5.3.2 Active Devices

Research was done to investigate the possibility of a controlled dc circuit in a special purpose winding on the transformer core [35]. This dc current tertiary winding would produce a counter MMF to that of the GIC. This method was however deemed non-successful by the investigators.

### 5.3.3 Operational Mitigation

Breaking the network into smaller sections can drastically reduce the flow of GICs, especially in a long interconnected network such as the Eskom MTS. However care has to be taken when using this method since blindly breaking the network could actually increase the GIC at certain substations due to the reduction of GIC terminating nodes.

The method is especially attractive for networks with series compensated lines. This is since taking out non-compensated lines can reduce the flow of GICs while still supplying sufficient power flow through series compensated lines. It is also the most cost- and time-effective method.

Operational mitigation is even more effective when the operators are given a lead-time to a geomagnetic storm. This is now possible through a company that predicts storm onset through observations from space (utilising the ACE satellite) of the formation of the Aurora Borealis. This service provides a lead-time of 30 to 45 minutes.

# Chapter 6

# Conclusions and Recommendations

Geomagnetic storms occur when the charged particles of the solar wind caused by a Coronal Mass Ejection on the sun are captured by the earth's dipole magnetic field. The perturbation of this magnetic field will cause an electric field on the earth's surface. This field is the source of GICs through the earthed transformer neutral. These storms are of a cyclic nature and peak every eleventh year.

The quasi dc GIC will cause an offset of the core magnetisation which could lead to half cycle saturation of a transformer if it supplies a big enough load. This could lead to all kinds of detrimental effects such as harmonics, reactive power swings, transformer overheating etc. This has happened in many countries at high latitude since they experience a more severe perturbation of the magnetic field than countries at mid latitude such as South Africa. However, the modelling does implicate that network configuration is as important factor as the induced electric field. Therefore utilities at mid-latitude such as Eskom could experience harmful GICs due to factors such as long-interconnected lines. The techniques to determine the effect of the network configuration and electric field were provided.

Eskom has been aware since about 1990, that occasional severe geomagnetic storms in the Southern Cape might disrupt the MTS in that area. At that time no correlation was observed between disruptions at selected sites of the Eskom MTS and geomagnetic activity. (The sites selected were based on the knowledge at that time.) However, an investigation into the past events on the Eskom MTS and correlation with geomagnetic storms have indicated that GICs may have caused damage to the extent of millions of

rands. Since this has happened during the previous solar peak (1991) to much time has passed and therefore detailed information was unavailable. This evidence suggests that the sites most susceptible are not at the conventionally accepted locations, and that damage and disruption may have occurred where it was not expected. Circumstantial evidence such as the failure of a reactor at Poseidon and Beta substations has been provided. The damage caused at these sites correlated very closely with geomagnetic storms and the extend of the damage is what is expected from GICs. It was also found that the core types of the power transformers generally used by Eskom are susceptible to GICs. Measurement techniques and mitigation methods were also provided, this could be applied to the Eskom MTS.

In light of the findings the following recommendations are made:

- Develop a complete network model and identify all the most sensitive locations
- Investigate for a correlation (if any) between the sites most susceptible from the theoretical modelling and past system events seemed to be caused by GICs
- Installation of monitors and sensors at most susceptible sites
- Train system controllers and develop a pro-active response so mitigation plans can be prepared as an operational mitigation technique
- Train network planners to apply mitigation techniques for future planning
- Review existing project implementation plans for installation of series capacitors to reduce the sensitivity of the network to GICs

This project provides information on the mechanism, impact and influencing factors of geomagnetically induced currents. The report also suggests that the Eskom MTS may be susceptible to it. Future research could establish the severity of GICs in the Eskom MTS and methods to reduce and even completely avoid its detrimental effects.

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# Appendix A

## GEOMAGNETICALLY INDUCED CURRENTS IN ESKOM'S MTS LITERATURE REVIEW

18 November 1999

### Introduction

This report has been prepared for Eskom Technology Group to serve as feedback on the literature review done by J Koen as part of the above-mentioned project, which commenced in January 1999. The review covered all three aspects of the project namely, astrophysics, geophysics and engineering.

This report is submitted through the Department of Electrical Engineering at the University of Cape Town and presents a bibliography of GIC literature relevant to the project.

### GIC Related Literature

This section lists the sources obtained to review the present understanding of mechanism of GICs and effects on power network equipment. The sources were mostly from journals. Other sources included theses, the Internet and reports.

A complete reference of a source is given in the list below, each followed by a short description of the information obtained or available through that source.

1. Viljanen, A., "Geomagnetic induction in a one- or two- dimensional earth due to horizontal ionospheric currents", Finnish Meteorological Institute Contributions, Helsinki, 1992.

*The thesis discusses the various methods available to calculate the secondary electric field due to geomagnetic induction.*

2. Kappenman, J.G., Albertson, V.D., "Bracing for the Geomagnetic Storms", IEEE Spectrum Magazine, pp. 27-33, March 1990.

*A good general introduction to GICs discussing the sun as source, why and how it effects power systems, and a description of the Hydro-Quebec blackout in March 1989.*

3. Pirjola, R., and Viljanen, A., "On Geomagnetically Induced Currents in the Finnish 400kV Power System by an Auroral Electrojet Current", IEEE Transactions on Power Delivery, Vol. 4, No.2, pp. 1239 – 1245, April 1989.

*The paper derives gives an expression to determine the earth surface electric field assuming a two-layered earth model.*

4. Kappenman, J.G., et al., "Geomagnetic Storms can Threaten Electric Power Grid", Earth in Space, Vol. 9, No. 7, pp. 9-11, March 1997.

*A good informative paper which discusses the potential disruption due to GICs as well as financial implications and forecasting methods for mitigation.*

5. Albertson, V., D., et al., "Load-Flow Studies in the Presence of Geomagnetically Induced Currents", IEEE Transactions on Power Apparatus and Systems, Vol. PAS-100, No. 2, pp. 594-607, February 1981.

*One of the first papers to discuss the modelling of a network to determine expected GIC magnitude. It presents the results of load flow analysis beginning with earth-surface potential and the modelling of the power system and transformers in a load flow program. The paper also elaborates on the implications of GICs on a network.*

6. Transmission and Distribution Committee Working Group on Geomagnetic Disturbances and Power System Effects, "Geomagnetic Disturbance Effects on Power Systems", IEEE Transactions on Power Delivery, Vol. 8, No. 3, pp. 1206-1215, July 1993

*The paper briefly discusses almost every single aspect of GICs. It is a very good summary of the source, effect and mitigation of GICs.*

7. Viljanen, A., and Pirjola, R., "Geomagnetically Induced Currents in the Finnish High Voltage Power System", Surveys in Geophysics, Vol. 15, pp. 383 – 408, 1994.

*Detailed discussion of the earth surface potential as calculated and measured in Finland.*

8. Sutcliffe, P.R., Kotze, P.B., "Proceedings of the Workshop on the Hermanus Magnetic Observatory's Geophysical Services", Hermanus Magnetic Observatory, pp. 1-61, February 1992.

*The notes describe the physics of geomagnetic storms and GICs. It also covers the severity of geomagnetic field variations in South Africa.*

9. Hruska, J., et al., "The major storm of 13-14 March 1989: Its character in Canada and some effects", STPW Proceedings, October 1989.

*A detailed description of the magnetic storm that led to the collapse of the Hydro-Quebec power system in March 1989.*

10. Viljanen, A., "The relation between geomagnetic variations and their time derivatives and implications for estimation if induction risks", Geophysical Research Letters, Vol. 24, No. 6, pp 631-634, March 15, 1997.

*The paper shows that the main concern during a geomagnetic storm is the rate of change of the magnetic field instead of the amplitude of the variation. It concludes that the geoelectric field can have large values in any direction, not only parallel to the electrojet.*

11. Viljanen, A., "Relation of Geomagnetically Induced Currents and Local Geomagnetic Variations", IEEE Transactions on Power Delivery, Vol. 13, No. 4, pp. 1285-1290, October 1998.

*A comparison of two models to calculate GICs from the time derivative of the magnetic field. The first model is a plane wave with homogenous earth and the second is an impulse response between the GIC and time derivative of the magnetic field. From this paper one can conclude that the former method should be an accurate way to model the Eskom MTS.*

12. Lehtinen, M., Pirjola, R., "Currents produced in earthed conductor networks by geomagnetically-induced electric fields", Annalas Geophysicae, Vol. 3, No. 4, pp. 479-484, 1985.

*A very good paper explaining the derivation of the matrix method necessary to complete the engineering step.*

13. Pirjola, R., Lehtinen, M., "Currents produced in the Finnish 400kV power transmission grid and in the Finnish natural gas pipeline by geomagnetically-induced electric fields", Annalas Geophysicae, Vol. 3, No. 4, pp. 485-491, 1985.

*This paper is a follow up of the previous mentioned paper. It describes the application of the matrix derived to determine GICs in the Finnish 400kV network.*

14. Elovaara, J., et al., "Geomagnetically Induced Currents in the Nordic Power System and their effects on Equipment, Control, Protection and Operation", Cigre, 1992.

*The paper compares the Finnish and Swedish Power Systems. The comparison was done since the Swedish grid have experienced may more disruption than in Finland although the countries are located next to each other. It is interesting to note that the Eskom network may be more similar to that of Sweden than Finland.*

15. Boteler, D.H., Bui-Van, Q., Lemay, J., "Directional sensitivity to geomagnetically induced currents of the Hydro-Quebec 735kV power system", IEEE Transactions on Power Delivery, Vol. 9, No. 4, October 1994.

*A description of a model used to calculate GICs. The model is then used to compare GIC magnitudes while varying the direction of the magnetic field. The results serve to indicate a possible worst case scenario.*

16. Towle, J.N., Prabhakara, F.S., Ponder, J.Z., "Geomagnetic effects modelling for the PJM interconnection system; Part I – Earth surface potentials computation", IEEE Transactions on Power Systems, Vol. 7, No. 3, August 1992.

*A description of the modelling of the Pennsylvania – New Jersey – Maryland (PJM) Interconnection to calculate GICs. This model is very complex since it consists of 11 different earth resistivity regions and a three dimensional ionospheric source.*

17. Prabhakara, F.S., et al., "Geomagnetic effects modelling for the PJM interconnection system; Part II – Geomagnetically induced current study results", IEEE Transactions on Power Systems, Vol. 7, No. 2, May 1992[1]

*This paper follows on the Towle et al one describing a method to calculate GICs. This was done for different ionospheric sources and used to compare different mitigation methods.*

18. Rackliffe, G.B., et al., "Simulation of Geomagnetic currents induced in a power system by magnetohydrodynamic eletromagnetic pulses", IEEE Transactions on Power Delivery, Vol. 3, No. 1, pp 392-397, January 1988.

*The paper discusses the effect of a magnetohydrodynamic-electromagnetic pulse (MHD-EMP) on a power system. This is of importance since it will produce quasi-dc currents in a power system, similar to a geomagnetic storm.*

19. Kappenman, J.G., "Geomagnetic Storms and Impacts on Power Systems: Lessons Learned from Solar Cycle 22 and Outlook for Solar Cycle 23", IEEE Power Engineering Review, May 1996

*This paper discusses the threat to power systems as well as the improvements in geomagnetic storm forecasting.*

20. Takasu, N., et al., "An experimental analysis if dc excitation of transformers by geomagnetically induced currents", IEEE Transactions on Power Delivery, Vol. 9, No. 2, April 1994.

*The paper discusses the results of excitation tests done on various small-scale transformer models. This was done by analysing the excitation current.*

21. Lu, S., Liu, Y., "FEM analysis of dc saturation to assess transformer susceptibility to geomagnetically induced currents", IEEE Transactions on Power Delivery, Vol. 8, No. 3, July 1993.

*The paper presents the result of a systematic finite element simulation of transformer susceptibility to GIC. It contributes to the understanding of transformer magnetisation due to GICs and the analysis is done on 5 different transformers.*

[1] although this is the second of the two papers it was published before part 1

22. Aspnes, J.D., Merritt, R.P., Akasofu, S.I., "Harmonic generation in transformers related to dc excitation and system loading", IEEE Transactions on Power Apparatus and Systems, Vol. PAS-100, No. 4, April 1981.

*A series of tests were run with small transformers to determine the harmonic generation from saturation.*

23. Aspnes, J.D., Akasofu, S.I., "Effect of Solar Induced Current on Autotransformer Tertiary Windings", IEEE Transactions on Power Apparatus and Systems, Vol. PAS-101, No. 3, March 1982.

*The discussion is on an Alaskan three-legged transformer and the reaction of the tertiary current to the neutral DC current. The protection of the transformer is also discussed.*

24. Douglas, D.A., "Current Transformer Accuracy with Asymmetric and High Frequency Fault Currents", IEEE Transactions on Power Apparatus and Systems, Vol. PAS-100, No. 3, pp 1006-1012, March 1981.

*Extensive discussion of CT modelling with some detail about saturation due to inrush which may be related to GIC.*

25. IEEE Communications Committee Working Group on Solar Effects, "Solar Effects on Communications", IEEE Transactions on Power Delivery, Vol. 7, No. 2, pp 460-467, April 1992.

*The paper considers the effect of geomagnetic storms on a different technology, communications. It also gives a good explanation of the cause of geomagnetic storms.*

26. Boteler, D.H., "Geomagnetically Induced Currents: Present Knowledge and Future Research", IEEE Transactions on Power Delivery, Vol. 9, No. 1, pp. 50–58, January 1994.

*The paper that provides a review of GICs in power systems. It then calculates the electric and magnetic field in a layered earth for Quebec during the March 1989, magnetic disturbance.*

27. Pirjola, R., "Induction in Power Transmission Lines During Geomagnetic Disturbances", Space Science Review, No. 35, pp 185-193, 1983.

*The paper elaborates about the calculation of the electric field. It also considers measurements of GICs at 4 different substations.*

28. Kappenman, J.G., Albertson, V.D., and Mohan, N., "Current Transformer and Relay Performance in the Presence of Geomagnetically-Induced Currents", IEEE Transactions on Power Apparatus and Systems, Vol. PAS-100, No. 3, pp. 1078-1088, March 1981.

*Extensive discussion of CT modelling and simulations including saturation characteristics.*

29. Albertson, V.D., "Electric and Magnetic Field at the Earth's Surface Due to Auroral Currents", IEEE Transactions on Power Apparatus and Systems, Vol. PAS-89, No. 4, pp. 578-584, April 1970.

*The paper considers the calculation of the electric and magnetic field at the surface of the earth.*

30. Kappenman, J.G., et al., "GIC Mitigation: A Neutral Blocking / Bypass Device to prevent the flow of GIC in Power Systems", IEEE Transactions on Power Delivery, Vol. 6, No. 3, pp. 1271–1281, July 1991.

*The paper discusses the possibility and performance of a capacitor in a transformer neutral as a blocking device for GIC.*

31. Boteler, D.H., Pirjola, R.J., Nevanlinna, H., "The Effects of Geomagnetic Disturbances on Electrical Systems at the Earth's Surface", Adv. Sapce Res., Vol. 22, No. 1, pp 17-27, 1998.

*The paper discusses the occurrence of geomagnetic storms, which is followed by an explanation of the susceptibility of a power system to the effects of such a storm.*

32. Mäkinen, T., "Geomagnetically Induced Currents in the Finnish Power Transmission System", Finnish Meteorological Institute, No. 32, p26, 1993.

*A very good paper on the prediction of GICs in the Finnish Power Grid based on measurements and theoretical models.*

33. Cigre, "Guide on EMC in Power Plants and Substations", Working Group 36.04, pp. 40–42, December 1997.

*A short general overview of GICs and their effects.*

34. Molinski, T.S., "Why Utilities Respect GICs", XXVIth General Assembly International Union of Radio Science, August 1999.

A very good paper giving a general overview and covering almost all aspects of GICs.

35. Technology Group Research Proposal, "Eskom/EPRI Sunburst 200 Collaboration: Geomagnetic Currents in Eskom's Southern Cape 400kV Network", Eskom, Report No TRR/CONS9/1998, 1998.

*The initial research proposal by Eskom used to approve the project. The proposal outlines the ultimate objectives of the research.*

36. Viljanen, A., Pirjola, R., "Statistics on Geomagnetically-Induced Currents in the Finnish 400kV Power System Based on Recordings of Geomagnetic Variations", Journal on Geomagnetism and Geoelectricity, Vol. 41, pp 411-420, 1989.

*A description of the Finnish system and the development of the earth surface potential.*

37. Girgis, R.S., Ko, C., "Calculation techniques and Results of GIC Currents as Applied to Two Large Power Transformers", IEEE Transactions on Power Delivery, Vol. 7, No.2, pp. 669–705, April 1992.

*A good description and analysis on the effect and mechanism of GICs inside transformers.*

38. Electric Research and Management, Inc., "SUNBURST GIC Network – Phase II Progress Report", Prepared for Electric Power Research Institute, February 1997.

*The report presents the progress of the Sunburst Network as well as technical discussions on the effect of GICs.*

39. Calabrò, S., Coppadoro, F., Crepaz, S., "The measurement of the magnetisation characteristics of large power transformers and reactors through D.C. excitation", IEEE Transactions on Power Delivery, Vol. 1, No.4, pp. 224– 234, October 1986.

*The paper discusses the non-linear magnetisation characteristics though dc excitation of both transformers and reactors.*

40. Aspnes, J.D., Merritt R.P., Spell, B.D., "Instrumentation Systems to Measure geomagnetically Induced Current Effect" IEEE Transactions on Power Delivery, Vol. 2, No.4, pp. 1031 – 1036, April 1989.

*The paper describes an instrumentation system that was used to measure the effects of GIC to the Alaska intertie.*

41. Pirjola, R., "On Currents Induced in Power Transmission Systems During Geomagnetic Variations", IEEE Transactions on Power Apparatus and Systems, Vol. PAS-104, No. 10, pp. 2825-2831, October 1985.

*The discussion concerns the calculation of the horizontal electric field and earth surface potential linking it to the varying geomagnetic fields from the electrojet.*

42. Pirjola, R., "Modelling the electric and magnetic fields at the Earth's surface due to an auroral electrojet", Journal of Atmospheric and Solar-Terrestrial Physics, No. 60, pp 1139-1148, 1998.

*The paper compares two models to calculate the electric and magnetic fields from the electrojet. The one model concerns the electrojet to be of infinite length and for the other model it has a finite length.*

43. Petschek, H., Feero, W., "Electric Power and Space Weather", Geomagnetic Applications Bulletin, pp 5 & 7, January 1997.

*A short article that serves to inform the reader of GICs, its effects and preventative steps.*

44. Appell, D., "Fire in the Sky", New Scientist, pp 29-32, 27 February 1999.

*A scientific report informing the reader of the source of GICs, its effects and modelling of the currents and electrojets.*

# Appendix B

**TRIP TO UNITED STATES AND SCANDINAVIA**
**BY**
**JACKO KOEN**

**27 September 1999 to 19 October 1999**

## 1 Introduction

The purpose of the visit was to hold technical discussions and undertake work with various researchers and Power Company Authorities on Geomagnetically Induced Currents (GICs) in power systems. The phenomenon and its possible effects on the Eskom MTS is not well understood and it was necessary to visit other researchers and utilities to strengthen the research being done by Eskom.

## 2 Itinerary

| Date | Location | Reason |
|---|---|---|
| Travel to Washington DC from Cape Town | | |
| 29/09/99 | Washington DC, USA | Attend Sunburst 2000 annual meeting |
| 30/09/99 | Washington DC, USA | Attend Sunburst 2000 annual meeting |
| Travel to Pittsburgh from Washington DC | | |
| 4/10/99 | Pittsburgh, USA | Attend Sunburst Workshop |
| 5/10/99 | Pittsburgh, USA | Attend Sunburst Workshop |
| Travel back to Washington DC and from there to Helsinki | | |
| 11/10/99 | Helsinki, Finland | Visit Finnish Meteorological Institute |
| 12/10/99 | Helsinki, Finland | Visit Finnish Meteorological Institute |
| 13/10/99 | Helsinki, Finland | Visit Finnish Meteorological Institute |
| 14/10/99 | Helsinki, Finland | Visit Fingrid Company |
| 15/10/99 | Helsinki, Finland | Visit Finnish Meteorological Institute |
| Travel to Stockholm from Helsinki | | |
| 18/10/99 | Stockholm, Sweden | Visit to Swedish National Grid |
| Travel from Stockholm to Helsinki and from there back to Cape Town | | |

## 3 United States.

### 3.1 Washington D.C.: Attending the Sunburst 2000 Annual Meeting

The purpose of this trip was as follows :
To attend the EPRI Sunburst 2000 Review Meeting in Washington, DC. As part of the approved TRI research project it was anticipated to take part in the EPRI Sunburst 2000 survey of GICs in large transmission systems world-wide. Since this participation is currently being reassessed, it served to investigate the technical and financial benefits of the proposed collaboration.

A major part of the meeting was a presentation and discussion of the SUNBURST-2000 project including progress made as well as a practical demonstration to illustrate the effectiveness of the hardware and software.
Some presentations at the meeting included:

- Strategy for Managing the Impact of GIC on the NGC Transmission System – Arslan Erinmez, NGC
- SpaceCast / PowerCast (a proposed mitigation technique by a warning in advance of a storm) – John Kappenman, Metatech
- Fingrid Transformer Test Plans and Update on the Complex Image Method – Risto Pirjola, Finnish Meteorological Institute (FMI)
- Space Weather Predictions / Forecasting – Brian Anderson and Dimitris Vassiliadis, NASA

### 3.2 Pittsburgh: Attending the Sunburst 2000 Workshop

The 2 day workshop served as an introduction to the Sunburst-2000 hardware and software. The workshop was presented by George Batrus of Electric Research. This company supplies and calibrates all the equipment needed to effectively measure GICs and its effects. Attending the workshop was successful from a financial perspective since the installation of the measuring equipment can now be done by the author, saving the costs of it being done by Electric Research.

### 3.3 Summary of visit to the USA

The trip was very successful in giving an insight into the progress and to receive up to date information as preparation for the occurrence of GICs. I found it surprising that many utilities who are very familiar with the effects of GICs are unprepared and ignoring the problem. I can only attribute this attitude to the fact that GICs occur mainly in 11 year cycles, causing a false comfort.

Although participating in the Sunburst 2000 program is quite costly this amount is minute compared to the possible financial implications due to GICs. Through participation one can accurately assess possible perturbations and then decide whether it is feasible to continue.

# 4 Scandinavia

## 4.1 Finland

### 4.1.1 Helsinki: Visit to the Finnish Meteorological Institute (FMI)

The purpose of this visit was to develop and test geomagnetic and engineering models of the Eskom grid. The author met with Prof. Risto Pirjola and Dr Ari Viljanen of the FMI. The FMI has been carrying out research of GICs, including their effects on power network equipment as well as measurements in transformer neutrals for more than 20 years. The FMI has also been participating in the EPRI SUNBURST project since 1994.

Geological, geomagnetic and engineering data from South Africa was discussed. It was decided to use the plane wave method assuming a homogenous earth to model the geoelectric field. A method to model autotransformers in the engineering step was also discussed. Two software programs for the geomagnetic and engineering models, based on the FMI models, were developed by the author and will be used for the Eskom grid.

### 4.1.2 Helsinki: Visit to the Fingrid Power Company

The author met with Mr Jarmo Elovaara of the Fingrid company. The company is responsible for the Finnish Transmission Lines. Their small personnel of 270 are responsible to manage the grid comprising of 100 substations and 14'000 km of transmission lines. They have experienced large GICs in their power network equipment and work closely with the FMI. One of their current projects is to asses the performance of a 3 phase, 5 limb transformer in the presence of GICs by injecting dc current into the neutral.

Although the company has measured very large GICs in the transformer neutrals they have not had severe incidents due to GICs. It has not caused any power system disturbances nor any equipment failure. However, there is clear evidence of transformer saturation due to GICs because of the increase in harmonic content in line currents as well as irregular fluctuations of reactive power. They believe that the excellent behaviour of the system during a geomagnetic storm is due to their transformer design where a lot of emphasis is put on the prevention of leakage flux. Another contributing factor is that almost all their transformers are used at less than 50% of rated load. They have identified the "hot spots" on their network and measurements are done at these sites on a full time basis to maintain the integrity of the network.

## 4.2 Sweden

### 4.2.1 Stockholm: Visit to the Svenska Kraftnät

The author met with Mr Bertil Kielen and Mr Lars Wallin of the Swedish National Grid. The company, who employs a staff of 235 people, is responsible for the transmission grid in Sweden. They have in the past experienced relay trips due to GICs; most of this is blamed on the old electromechanical overcurrent relays used at that time. These relays did not have any stabilisation against the 100Hz harmonic. Another factor which decreased the networks susceptibility to GICs is that they use series capacitors in most of their longer lines, effectively blocking the quasi-dc GICs.

At this time only one site is being monitored. It is a generator step-up transformer at a nuclear power station. Through past events it seems that this site experience the highest magnitude of GICs. When the measured value at this site exceeds a certain threshold it will set an alarm at the Swedish National Control to make the operators aware of a possible problem. They will then be conscious of a possible problem (such as increase in MVAR demand, voltage or frequency swing, etc.) and if required disconnect the transformer. This system has been in operation following the previous cycle and to date such an action has not been necessary, taking in mind that this was during a solar minimum period.

## 4.3 Summary of visit to Scandinavia

The visit to the FMI was very successful in understanding the modelling of a power grid and to calculate the flow of GICs. Other benefits were the exposure to their established experience and guidance concerning the measurement of currents and the effect of the currents on the high voltage equipment.

The researchers at the FMI have been very helpful since the start of this project. Once again they went through a lot of trouble to help and give guidance. The visit to the FMI has helped to understand and apply some of the essential steps to complete both the engineering and geophysical step.

The Fingrid company is very aware of GICs and have measured them for more than 20 years. However, they have not incorporated any mitigation techniques to date since they have not experienced any major disturbances such as the blackout in Canada during March 1989. They do not anticipate any problems due to overheating of transformers but are aware that the saturation of more than one transformer could cause the reactive power demand to cause problems.

The Swedish National Grid does not seem to be too concerned with GICs. Apart from the measurements at a selected site they do not have any other formal mitigation techniques. They are satisfied through past experience that it is only necessary to monitor GICs at a selected site and react if necessary.

# Appendix C

## Data of Geomagnetic Activity (K-index) for Period 1/01/89 – 31/12/92

Major to severe storms (i.e. K ≥ 6) are indicated in bold

| Year | Date | | K-index | |
|---|---|---|---|---|
| 1989 | 1 | January | 3122 | 2132 |
| | 2 | January | 1122 | 2221 |
| | 3 | January | 22 | 1122 |
| | 4 | January | 1033 | 2234 |
| | 5 | January | 4443 | 4552 |
| | 6 | January | 2223 | 1123 |
| | 7 | January | 4233 | 2321 |
| | 8 | January | 1133 | 3333 |
| | 9 | January | 2222 | 4333 |
| | 10 | January | 2231 | 3321 |
| | 11 | January | 1121 | **4666** |
| | 12 | January | 4322 | 2121 |
| | 13 | January | 2 | 4433 |
| | 14 | January | 3311 | 2234 |
| | 15 | January | 3434 | 4455 |
| | 16 | January | 3334 | 3535 |
| | 17 | January | 3334 | 5342 |
| | 18 | January | 4233 | 3211 |
| | 19 | January | 2120 | 122 |
| | 20 | January | 2134 | **7754** |
| | 21 | January | 3233 | 3444 |
| | 22 | January | 4333 | 4323 |
| | 23 | January | 2243 | 4323 |
| | 24 | January | 1122 | 2332 |
| | 25 | January | 1023 | 3232 |
| | 26 | January | 2223 | 2211 |
| | 27 | January | 2123 | 3211 |
| | 28 | January | 1212 | 2232 |
| | 29 | January | 2122 | 3321 |
| | 30 | January | 1212 | 2222 |
| | 31 | January | 2122 | **2366** |
| | | | | |
| | 1 | February | 4324 | 4235 |
| | 2 | February | 4320 | 3344 |
| | 3 | February | 4534 | 4454 |
| | 4 | February | 4322 | 4244 |
| | 5 | February | 3223 | 2334 |
| | 6 | February | 3232 | 3332 |
| | 7 | February | 3224 | 3233 |
| | 8 | February | 3222 | 2223 |
| | 9 | February | 3322 | 3233 |
| | 10 | February | 3212 | 2010 |
| | 11 | February | 1023 | 2342 |
| | 12 | February | 2112 | 2343 |
| | 13 | February | 3344 | 3442 |
| | 14 | February | 2232 | 3310 |
| | 15 | February | 1111 | 1244 |
| | 16 | February | 4423 | 3123 |
| | 17 | February | 2222 | 2011 |
| | 18 | February | 1210 | 3431 |
| | 19 | February | 122 | 2323 |
| | 20 | February | 2343 | 3331 |
| | 21 | February | 2133 | 2311 |
| | 22 | February | 1133 | 2222 |
| | 23 | February | 1122 | 2 |
| | 24 | February | 2223 | 2111 |
| | 25 | February | 22 | 1011 |
| | 26 | February | 1011 | 1001 |
| | 27 | February | 1112 | 2201 |
| | 28 | February | 233 | 3334 |
| | | | | |
| | 1 | March | 3223 | 3222 |
| | 2 | March | 3534 | 4232 |
| | 3 | March | 2344 | 3442 |
| | 4 | March | 3113 | 3300 |
| | 5 | March | 3345 | 4333 |
| | 6 | March | 3234 | **6533** |
| | 7 | March | 3323 | 2212 |
| | 8 | March | 2110 | **465** |
| | 9 | March | 4422 | 3334 |
| | 10 | March | 3332 | 2222 |
| | 11 | March | 2233 | 2234 |
| | 12 | March | 4223 | 4543 |
| | 13 | March | **5679** | **7889** |
| | 14 | March | **9765** | **3466** |
| | 15 | March | **6443** | 3332 |
| | 16 | March | 1445 | 5343 |
| | 17 | March | 4343 | 3322 |
| | 18 | March | 222 | 3301 |
| | 19 | March | **1264** | 5333 |
| | 20 | March | 1322 | 3323 |
| | 21 | March | 4243 | 2133 |
| | 22 | March | 3233 | 4555 |
| | 23 | March | 3224 | 3434 |
| | 24 | March | 4332 | 1101 |
| | 25 | March | 1122 | 233 |
| | 26 | March | 2213 | 3224 |
| | 27 | March | 3253 | **5634** |
| | 28 | March | **5336** | 5434 |
| | 29 | March | 5444 | **4366** |
| | 30 | March | 4553 | 2244 |
| | 31 | March | 4543 | 4444 |
| | | | | |
| | 1 | April | 5333 | 3454 |
| | 2 | April | 3333 | 3422 |

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|---|---|---|---|---|
| | 3 | April | 4323 | 2234 |
| | 4 | April | 4345 | 5445 |
| | 5 | April | 5334 | 3354 |
| | 6 | April | 4322 | 2232 |
| | 7 | April | 1143 | 4334 |
| | 8 | April | 4323 | 3432 |
| | 9 | April | 4223 | 2342 |
| | 10 | April | 3011 | 2132 |
| | 11 | April | 1222 | 4432 |
| | 12 | April | 2121 | 1112 |
| | 13 | April | 1243 | 2223 |
| | 14 | April | 3132 | 2455 |
| | 15 | April | 4533 | 2221 |
| | 16 | April | 1120 | 3354 |
| | 17 | April | 4012 | 1211 |
| | 18 | April | 3313 | 1000 |
| | 19 | April | 1022 | 2211 |
| | 20 | April | 2222 | 1222 |
| | 21 | April | 2232 | 2210 |
| | 22 | April | 3101 | 2112 |
| | 23 | April | 2122 | 2442 |
| | 24 | April | 3103 | 3213 |
| | 25 | April | 2234 | 3555 |
| | 26 | April | 5554 | 4454 |
| | 27 | April | **6544** | 2444 |
| | 28 | April | 4333 | 3344 |
| | 29 | April | 2344 | 3344 |
| | 30 | April | 3232 | 2232 |
| | | | | |
| | 1 | May | 3112 | 1223 |
| | 2 | May | 3333 | 2243 |
| | 3 | May | 3222 | 2123 |
| | 4 | May | 4321 | 2334 |
| | 5 | May | 5544 | 1143 |
| | 6 | May | 2323 | 1133 |
| | 7 | May | 444 | 4345 |
| | 8 | May | 2011 | 13 |
| | 9 | May | 1010 | 2100 |
| | 10 | May | 1000 | 2 |
| | 11 | May | 11 | 122 |
| | 12 | May | 2232 | 1221 |
| | 13 | May | 113 | 4310 |
| | 14 | May | 1322 | 1211 |
| | 15 | May | 1132 | 1232 |
| | 16 | May | 1222 | 1211 |
| | 17 | May | 1222 | 1111 |
| | 18 | May | 1222 | 2210 |
| | 19 | May | 12 | 1211 |
| | 20 | May | 1015 | 4220 |
| | 21 | May | 1122 | 2111 |
| | 22 | May | 2122 | 3223 |
| | 23 | May | 2212 | **5646** |
| | 24 | May | 5454 | 5544 |
| | 25 | May | 4232 | 2233 |
| | 26 | May | 2113 | 3334 |

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|---|---|---|---|---|
| | 27 | May | 3333 | 2233 |
| | 28 | May | 2312 | 3332 |
| | 29 | May | 4233 | 3322 |
| | 30 | May | 3221 | 1022 |
| | 31 | May | 3122 | 2123 |
| | | | | |
| | 1 | June | 3212 | 2122 |
| | 2 | June | 1123 | 4133 |
| | 3 | June | 3311 | 3323 |
| | 4 | June | 4401 | 1001 |
| | 5 | June | 1021 | 112 |
| | 6 | June | 2222 | 2104 |
| | 7 | June | 5445 | 4023 |
| | 8 | June | 3222 | 2044 |
| | 9 | June | 5423 | 2255 |
| | 10 | June | 4444 | 4544 |
| | 11 | June | 4333 | 2222 |
| | 12 | June | 3232 | 2110 |
| | 13 | June | 1022 | 1333 |
| | 14 | June | 2345 | 4344 |
| | 15 | June | 5443 | 3433 |
| | 16 | June | 3322 | 1000 |
| | 17 | June | 2 | 111 |
| | 18 | June | 1 | 1110 |
| | 19 | June | 22 | 1122 |
| | 20 | June | 2223 | 3343 |
| | 21 | June | 11 | 1 |
| | 22 | June | 10 | 1011 |
| | 23 | June | 1012 | 1111 |
| | 24 | June | 1123 | 3102 |
| | 25 | June | 1212 | 1101 |
| | 26 | June | 22 | 2222 |
| | 27 | June | 2101 | 1002 |
| | 28 | June | 2112 | 1101 |
| | 29 | June | 3322 | 1222 |
| | 30 | June | 3322 | 11 |
| | | | | |
| | 1 | July | 1032 | **1643** |
| | 2 | July | 3120 | 0 |
| | 3 | July | 11 | 0 |
| | 4 | July | 11 | 1000 |
| | 5 | July | 1002 | 1233 |
| | 6 | July | 2212 | 2221 |
| | 7 | July | 1121 | 1010 |
| | 8 | July | 10 | 0 |
| | 9 | July | 2100 | 1011 |
| | 10 | July | 1223 | 1223 |
| | 11 | July | 1001 | 0 |
| | 12 | July | 1 | 1 |
| | 13 | July | 30 | 110 |
| | 14 | July | 0 | 121 |
| | 15 | July | 12 | 1110 |
| | 16 | July | 0 | 0 |
| | 17 | July | 3232 | 2331 |
| | 18 | July | 3322 | 1222 |

| | | | | |
|---|---|---|---|---|
| | 19 | July | 1100 | 0 |
| | 20 | July | 12 | 102 |
| | 21 | July | 1112 | 1 |
| | 22 | July | 1001 | 2002 |
| | 23 | July | 1312 | 3311 |
| | 24 | July | 2013 | 2211 |
| | 25 | July | 1132 | 2103 |
| | 26 | July | 1122 | 2222 |
| | 27 | July | 2221 | 213 |
| | 28 | July | 2112 | 1123 |
| | 29 | July | 3123 | 1223 |
| | 30 | July | 1021 | 112 |
| | 31 | July | 1011 | 1001 |
| | | | | |
| | 1 | August | 1010 | 1112 |
| | 2 | August | 3110 | 1 |
| | 3 | August | 2222 | 1000 |
| | 4 | August | 12 | 2122 |
| | 5 | August | 1000 | 1 |
| | 6 | August | 1001 | 1222 |
| | 7 | August | 1122 | 3222 |
| | 8 | August | 2222 | 12 |
| | 9 | August | 2012 | 1143 |
| | 10 | August | 3355 | 3344 |
| | 11 | August | 4424 | 3312 |
| | 12 | August | 3122 | 3102 |
| | 13 | August | 3321 | 2111 |
| | 14 | August | **3366** | 5335 |
| | 15 | August | 5543 | **5336** |
| | 16 | August | 5522 | 2123 |
| | 17 | August | 3222 | 3544 |
| | 18 | August | 5444 | 3343 |
| | 19 | August | 3411 | 1120 |
| | 20 | August | 1244 | 5411 |
| | 21 | August | 2111 | 2445 |
| | 22 | August | 4332 | 11 |
| | 23 | August | 2323 | 4544 |
| | 24 | August | 3021 | 1001 |
| | 25 | August | 11 | 1212 |
| | 26 | August | 122 | 0 |
| | 27 | August | 2433 | **4364** |
| | 28 | August | 2012 | 1245 |
| | 29 | August | **6642** | 3331 |
| | 30 | August | 2323 | 3333 |
| | 31 | August | 2010 | 1222 |
| | | | | |
| | 1 | September | 2220 | 1000 |
| | 2 | September | 2222 | 1210 |
| | 3 | September | 1321 | 2012 |
| | 4 | September | 5444 | 2003 |
| | 5 | September | 3353 | 1021 |
| | 6 | September | 2222 | 2321 |
| | 7 | September | 2023 | 3533 |
| | 8 | September | 4432 | 1212 |
| | 9 | September | 2113 | 3233 |

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|---|---|---|---|---|
| | 10 | September | 2222 | 2321 |
| | 11 | September | 2 | 2 |
| | 12 | September | 2233 | 2101 |
| | 13 | September | 1122 | 2223 |
| | 14 | September | 1123 | 2000 |
| | 15 | September | 3423 | **4466** |
| | 16 | September | 4331 | 2222 |
| | 17 | September | 2010 | 1023 |
| | 18 | September | 3234 | **3466** |
| | 19 | September | **5653** | 3230 |
| | 20 | September | 101 | 1111 |
| | 21 | September | 2221 | 1001 |
| | 22 | September | 245 | 4333 |
| | 23 | September | 2010 | 102 |
| | 24 | September | 22 | 2122 |
| | 25 | September | 1100 | 1111 |
| | 26 | September | 135 | **4666** |
| | 27 | September | 3022 | 2000 |
| | 28 | September | 2100 | 1222 |
| | 29 | September | 2112 | 1322 |
| | 30 | September | 2202 | 1354 |
| | | | | |
| | 1 | October | 2222 | 2212 |
| | 2 | October | 1433 | 3210 |
| | 3 | October | 1134 | 3432 |
| | 4 | October | 2111 | 1122 |
| | 5 | October | 2101 | 1111 |
| | 6 | October | 1034 | 2213 |
| | 7 | October | 3222 | 2222 |
| | 8 | October | 2223 | 1003 |
| | 9 | October | 3322 | 2113 |
| | 10 | October | 3322 | 2311 |
| | 11 | October | 2233 | 2211 |
| | 12 | October | 1233 | 2112 |
| | 13 | October | 1100 | 0 |
| | 14 | October | 0 | 1000 |
| | 15 | October | 201 | 2130 |
| | 16 | October | 1123 | 3121 |
| | 17 | October | 2223 | 1021 |
| | 18 | October | 4324 | 3333 |
| | 19 | October | 5444 | 4120 |
| | 20 | October | 2335 | **7775** |
| | 21 | October | **4567** | **6566** |
| | 22 | October | 4423 | 3444 |
| | 23 | October | 3431 | 2343 |
| | 24 | October | 2243 | 2333 |
| | 25 | October | 3332 | 1102 |
| | 26 | October | 2322 | 4454 |
| | 27 | October | 4234 | 3232 |
| | 28 | October | 1122 | 1432 |
| | 29 | October | 1222 | 2234 |
| | 30 | October | 3233 | 2233 |
| | 31 | October | 3222 | 4131 |
| | | | | |
| | 1 | November | 1112 | 1223 |

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|---|---|---|---|---|
| | 2 | November | 4332 | 2343 |
| | 3 | November | 4244 | 4232 |
| | 4 | November | 2134 | 4335 |
| | 5 | November | 5233 | 1144 |
| | 6 | November | 2112 | 3231 |
| | 7 | November | 3334 | 5223 |
| | 8 | November | 2224 | 3430 |
| | 9 | November | 4444 | 3541 |
| | 10 | November | 2343 | 2322 |
| | 11 | November | 4344 | 4354 |
| | 12 | November | 3332 | 2123 |
| | 13 | November | 3444 | 4554 |
| | 14 | November | 3333 | 2223 |
| | 15 | November | 2032 | 2211 |
| | 16 | November | 1012 | 3221 |
| | 17 | November | 2337 | **6767** |
| | 18 | November | **6443** | 2122 |
| | 19 | November | 33 | 343 |
| | 20 | November | 1113 | 2232 |
| | 21 | November | 3144 | 3101 |
| | 22 | November | 111 | 2321 |
| | 23 | November | 3101 | 11 |
| | 24 | November | 231 | 1112 |
| | 25 | November | 2300 | 0 |
| | 26 | November | 1024 | 1333 |
| | 27 | November | 2222 | 3334 |
| | 28 | November | 4443 | 4435 |
| | 29 | November | 4334 | 3343 |
| | 30 | November | 3212 | 4244 |
| | | | | |
| | 1 | December | 4323 | **4565** |
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| | 3 | December | 4335 | 3333 |
| | 4 | December | 4433 | 3335 |
| | 5 | December | 4210 | 121 |
| | 6 | December | 2100 | 2111 |
| | 7 | December | 2222 | 233 |
| | 8 | December | 1122 | 2012 |
| | 9 | December | 1112 | 1020 |
| | 10 | December | 10 | 10 |
| | 11 | December | 122 | 3211 |
| | 12 | December | 1121 | 2113 |
| | 13 | December | 2223 | 2120 |
| | 14 | December | 13 | 4332 |
| | 15 | December | 2123 | 2222 |
| | 16 | December | 1124 | 3323 |
| | 17 | December | 2224 | 3211 |
| | 18 | December | 1033 | 2133 |
| | 19 | December | 3212 | 3021 |
| | 20 | December | 1222 | 2222 |
| | 21 | December | 3222 | 2221 |
| | 22 | December | 3344 | **5463** |
| | 23 | December | 3434 | 3222 |
| | 24 | December | 2223 | 3443 |
| | 25 | December | 3232 | 2234 |
| | 26 | December | 2133 | 3354 |
| | 27 | December | 3323 | 4433 |
| | 28 | December | 3322 | 2213 |
| | 29 | December | 2244 | 4555 |
| | 30 | December | 4232 | 2334 |
| | 31 | December | 4334 | 3434 |

| Year | Date | | K-index | |
|---|---|---|---|---|
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| | 3 | January | 3222 | 1331 |
| | 4 | January | 2013 | 2223 |
| | 5 | January | 3122 | 2343 |
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| | 7 | January | 2121 | 1001 |
| | 8 | January | 1112 | 4543 |
| | 9 | January | 3232 | 3212 |
| | 10 | January | 3233 | 2333 |
| | 11 | January | 2234 | 4343 |
| | 12 | January | 3224 | 3232 |
| | 13 | January | 2123 | 2101 |
| | 14 | January | 12 | 3211 |
| | 15 | January | 1111 | 2310 |
| | 16 | January | 1133 | 1233 |
| | 17 | January | 2221 | 1212 |
| | 18 | January | 2013 | 3112 |
| | 19 | January | 1001 | 1022 |
| | 20 | January | 3243 | 3332 |
| | 21 | January | 3334 | 4342 |
| | 22 | January | 3324 | 3233 |
| | 23 | January | 3423 | 3333 |
| | 24 | January | 3443 | 3344 |
| | 25 | January | 4333 | 2211 |
| | 26 | January | 2123 | 2330 |
| | 27 | January | 1110 | 210 |
| | 28 | January | 22 | 3334 |
| | 29 | January | 4342 | 4233 |
| | 30 | January | 4432 | 4443 |
| | 31 | January | 3333 | 3331 |
| | | | | |
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| | 2 | February | 3333 | 4443 |
| | 3 | February | 2102 | 1332 |
| | 4 | February | 3323 | **3663** |
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| | 6 | February | 2221 | 1111 |
| | 7 | February | 223 | 3445 |
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| | 10 | February | 1032 | 3211 |
| | 11 | February | 1232 | 3222 |
| | 12 | February | 3123 | 1000 |
| | 13 | February | 102 | 1313 |
| | 14 | February | 4445 | 3211 |
| | 15 | February | 2244 | **4456** |
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| | 17 | February | 5323 | 3334 |
| | 18 | February | 3234 | 3334 |
| | 19 | February | 4334 | 4445 |
| | 20 | February | 4443 | 5354 |
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| | 28 | February | 3433 | 4242 |
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| | 1 | March | 4323 | 3334 |
| | 2 | March | 2233 | 2233 |
| | 3 | March | 2222 | 3232 |
| | 4 | March | 22 | 1012 |
| | 5 | March | 3212 | 1103 |
| | 6 | March | 4443 | 3211 |
| | 7 | March | 2223 | 3202 |
| | 8 | March | 2113 | 3211 |
| | 9 | March | 2124 | 2112 |
| | 10 | March | 1122 | 3121 |
| | 11 | March | 3233 | 2321 |
| | 12 | March | 2233 | **3566** |
| | 13 | March | **6423** | 2234 |
| | 14 | March | 5335 | 3321 |
| | 15 | March | 3112 | 1133 |
| | 16 | March | 3122 | 1022 |
| | 17 | March | 1021 | 0 |
| | 18 | March | 1134 | 4455 |
| | 19 | March | 5212 | 1112 |
| | 20 | March | 3223 | **3336** |
| | 21 | March | **6345** | 4453 |
| | 22 | March | 4233 | 3344 |
| | 23 | March | 3333 | 3343 |
| | 24 | March | 3323 | 3244 |
| | 25 | March | 3334 | 4344 |
| | 26 | March | 5333 | 3443 |
| | 27 | March | 4443 | 2355 |
| | 28 | March | 3323 | 3233 |
| | 29 | March | 3313 | 3325 |
| | 30 | March | **3365** | 4322 |
| | 31 | March | 2111 | 1012 |
| | | | | |
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| | 2 | April | 223 | 3222 |
| | 3 | April | 1223 | 4333 |
| | 4 | April | 3123 | 3220 |
| | 5 | April | 23 | 4220 |
| | 6 | April | 123 | 2112 |
| | 7 | April | 1133 | 2211 |
| | 8 | April | 2102 | 2111 |
| | 9 | April | 1145 | 4432 |
| | 10 | April | **3346** | **7675** |
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| | 12 | April | **3664** | 5554 |
| | 13 | April | 5343 | 3444 |
| | 14 | April | 4444 | 3334 |
| | 15 | April | 3432 | 3231 |
| | 16 | April | 2121 | 2022 |
| | 17 | April | 4245 | 5344 |

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| | 19 | April | 2121 | 1233 |
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| | 21 | April | 4432 | 1001 |
| | 22 | April | 2332 | 1324 |
| | 23 | April | 3444 | 3433 |
| | 24 | April | 2243 | 3223 |
| | 25 | April | 3333 | 2223 |
| | 26 | April | 3421 | 1101 |
| | 27 | April | 2432 | 1224 |
| | 28 | April | 3233 | 3243 |
| | 29 | April | 3344 | 2234 |
| | 30 | April | **6323** | 1113 |
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| | 1 | May | 2212 | 2120 |
| | 2 | May | 124 | 2112 |
| | 3 | May | 2214 | 3233 |
| | 4 | May | 3123 | 3322 |
| | 5 | May | 2123 | 1130 |
| | 6 | May | 121 | 1011 |
| | 7 | May | 1021 | 1200 |
| | 8 | May | 1222 | 2213 |
| | 9 | May | 2233 | 3134 |
| | 10 | May | 3444 | 3342 |
| | 11 | May | 4333 | 3223 |
| | 12 | May | 4101 | 1 |
| | 13 | May | 112 | 3322 |
| | 14 | May | 110 | 10 |
| | 15 | May | 1002 | 3010 |
| | 16 | May | 10 | 1000 |
| | 17 | May | 112 | 0 |
| | 18 | May | 2143 | 4434 |
| | 19 | May | 4422 | 4324 |
| | 20 | May | 2323 | 3343 |
| | 21 | May | 3203 | 4433 |
| | 22 | May | 3344 | 4333 |
| | 23 | May | 3122 | 212 |
| | 24 | May | 0 | 101 |
| | 25 | May | 3223 | 3323 |
| | 26 | May | 4313 | **4346** |
| | 27 | May | 3554 | 3422 |
| | 28 | May | 112 | 1211 |
| | 29 | May | 1022 | 2214 |
| | 30 | May | 3324 | 3243 |
| | 31 | May | 3212 | 1132 |
| | | | | |
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| | 2 | June | 1011 | 1100 |
| | 3 | June | 1111 | 1011 |
| | 4 | June | 101 | 0 |
| | 5 | June | 1 | 1011 |
| | 6 | June | 2222 | 1223 |
| | 7 | June | 3333 | 2122 |
| | 8 | June | 2423 | 134 |
| | 9 | June | 3353 | 4322 |

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| | 10 | June | 4222 | 3214 |
| | 11 | June | 3212 | 2123 |
| | 12 | June | 4335 | **3566** |
| | 13 | June | **6554** | 5432 |
| | 14 | June | 4535 | **6433** |
| | 15 | June | 2322 | 1113 |
| | 16 | June | 3000 | 0 |
| | 17 | June | 10 | 0 |
| | 18 | June | 23 | 2333 |
| | 19 | June | 2210 | 1000 |
| | 20 | June | 0 | 1 |
| | 21 | June | 1 | 21 |
| | 22 | June | 2210 | 1 |
| | 23 | June | 1011 | 1200 |
| | 24 | June | 12 | 1111 |
| | 25 | June | 1122 | 2011 |
| | 26 | June | 1112 | 1101 |
| | 27 | June | 1022 | 2113 |
| | 28 | June | 2122 | 1100 |
| | 29 | June | 121 | 2110 |
| | 30 | June | 1000 | 1 |
| | | | | |
| | 1 | July | 1000 | 13 |
| | 2 | July | 3310 | 0 |
| | 3 | July | 1211 | 1000 |
| | 4 | July | 1022 | 322 |
| | 5 | July | 1202 | 1122 |
| | 6 | July | 1001 | 21 |
| | 7 | July | 10 | 13 |
| | 8 | July | 312 | 1213 |
| | 9 | July | 2111 | 2100 |
| | 10 | July | 323 | 3111 |
| | 11 | July | 120 | 1030 |
| | 12 | July | 1132 | 1003 |
| | 13 | July | 2333 | 123 |
| | 14 | July | 2021 | 2232 |
| | 15 | July | 2321 | 120 |
| | 16 | July | 3100 | 1021 |
| | 17 | July | 100 | 3 |
| | 18 | July | 2020 | 1120 |
| | 19 | July | 1223 | 3223 |
| | 20 | July | 2233 | 2222 |
| | 21 | July | 2010 | 21 |
| | 22 | July | 1110 | 1001 |
| | 23 | July | 1100 | 11 |
| | 24 | July | 102 | 0 |
| | 25 | July | 1012 | 1000 |
| | 26 | July | 11 | 1132 |
| | 27 | July | 1222 | 1021 |
| | 28 | July | **2456** | **6566** |
| | 29 | July | 5544 | 4324 |
| | 30 | July | 2222 | 123 |
| | 31 | July | 3021 | 0 |
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| | 1 | August | 32 | 4343 |

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| | 2 | August | 3221 | 2 |
| | 3 | August | 2122 | 2033 |
| | 4 | August | 3120 | 2010 |
| | 5 | August | 1001 | 1102 |
| | 6 | August | 2112 | 1232 |
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| | 8 | August | 1220 | 0 |
| | 9 | August | 2001 | 100 |
| | 10 | August | 111 | 111 |
| | 11 | August | 3132 | 2001 |
| | 12 | August | 2212 | 2 |
| | 13 | August | 2323 | 2221 |
| | 14 | August | 2244 | 2223 |
| | 15 | August | 2114 | 3334 |
| | 16 | August | 3244 | 3324 |
| | 17 | August | 4331 | 1332 |
| | 18 | August | 2322 | 2202 |
| | 19 | August | 4321 | 3113 |
| | 20 | August | 2432 | 2230 |
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| | 22 | August | 3443 | 3324 |
| | 23 | August | 4333 | 4543 |
| | 24 | August | 3443 | 3200 |
| | 25 | August | 1010 | 122 |
| | 26 | August | 2355 | 5433 |
| | 27 | August | 4332 | 4221 |
| | 28 | August | 2122 | 2100 |
| | 29 | August | 1123 | 2142 |
| | 30 | August | 3223 | 4433 |
| | 31 | August | 4223 | 2111 |
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| | 1 | September | 2314 | 4431 |
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| | 3 | September | 11 | 10 |
| | 4 | September | 1012 | 1323 |
| | 5 | September | 4222 | 2112 |
| | 6 | September | 3143 | 2221 |
| | 7 | September | 3233 | 3211 |
| | 8 | September | 1122 | 133 |
| | 9 | September | 1212 | 1123 |
| | 10 | September | 3120 | 123 |
| | 11 | September | 2244 | 3345 |
| | 12 | September | 3333 | 2143 |
| | 13 | September | 4133 | 3323 |
| | 14 | September | 4334 | 3332 |
| | 15 | September | 3334 | 4331 |
| | 16 | September | 4345 | 4212 |
| | 17 | September | 2232 | 1123 |
| | 18 | September | 123 | 2243 |
| | 19 | September | 4223 | 1423 |
| | 20 | September | 4101 | 1345 |
| | 21 | September | 3123 | 2223 |
| | 22 | September | 3332 | 2233 |
| | 23 | September | 3333 | 1221 |
| | 24 | September | 1232 | 2222 |

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|---|---|---|---|---|
| | 25 | September | 4322 | 43 |
| | 26 | September | 2123 | 2221 |
| | 27 | September | 3211 | 2111 |
| | 28 | September | 2212 | 2112 |
| | 29 | September | 2112 | 2012 |
| | 30 | September | 2101 | 1011 |
| | | | | |
| | 1 | October | 1111 | 1 |
| | 2 | October | 1011 | 2221 |
| | 3 | October | 2222 | 2223 |
| | 4 | October | 1233 | 3332 |
| | 5 | October | 2233 | 3212 |
| | 6 | October | 2233 | 2222 |
| | 7 | October | 1122 | 2233 |
| | 8 | October | 11 | 2111 |
| | 9 | October | 1012 | 4543 |
| | 10 | October | **5464** | 4222 |
| | 11 | October | 5254 | 5345 |
| | 12 | October | 3433 | 2333 |
| | 13 | October | 3222 | 2233 |
| | 14 | October | 3232 | 2334 |
| | 15 | October | 3323 | 3343 |
| | 16 | October | 2122 | 1233 |
| | 17 | October | 1111 | 1001 |
| | 18 | October | 1 | 1121 |
| | 19 | October | 3223 | 1123 |
| | 20 | October | 1233 | 5534 |
| | 21 | October | 3232 | 2010 |
| | 22 | October | 3332 | 2111 |
| | 23 | October | 1122 | 2233 |
| | 24 | October | 4434 | 4131 |
| | 25 | October | 3212 | 2112 |
| | 26 | October | 2014 | 3432 |
| | 27 | October | 1202 | 1111 |
| | 28 | October | 1132 | 0 |
| | 29 | October | 103 | 3243 |
| | 30 | October | 5222 | 2233 |
| | 31 | October | 1232 | 3453 |
| | | | | |
| | 1 | November | 1222 | 1213 |
| | 2 | November | 2321 | 1123 |
| | 3 | November | 1213 | 2111 |
| | 4 | November | 1011 | 0 |
| | 5 | November | 0 | 1 |
| | 6 | November | 113 | 11 |
| | 7 | November | 22 | 2221 |
| | 8 | November | 22 | 2222 |
| | 9 | November | 2232 | 2112 |
| | 10 | November | 2123 | 2122 |
| | 11 | November | 1133 | 3121 |
| | 12 | November | 2302 | 1112 |
| | 13 | November | 1121 | 110 |
| | 14 | November | 1 | 1000 |
| | 15 | November | 1012 | 121 |
| | 16 | November | 3132 | 3333 |

| | | | | |
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| | 17 | November | 1233 | 3432 |
| | 18 | November | 4302 | 3332 |
| | 19 | November | 3322 | 1212 |
| | 20 | November | 2212 | 2122 |
| | 21 | November | 2212 | 3121 |
| | 22 | November | 21 | 1020 |
| | 23 | November | 111 | 1101 |
| | 24 | November | 1000 | 1000 |
| | 25 | November | 1022 | 1111 |
| | 26 | November | 2132 | 3004 |
| | 27 | November | 4234 | **5653** |
| | 28 | November | 3322 | 2241 |
| | 29 | November | 1111 | 121 |
| | 30 | November | 1012 | 2421 |
| | | | | |
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| | 2 | December | 112 | 2221 |
| | 3 | December | 11 | 1233 |
| | 4 | December | 3322 | 3323 |
| | 5 | December | 2122 | 2331 |
| | 6 | December | 1122 | 2111 |
| | 7 | December | 1111 | 1210 |
| | 8 | December | 12 | 3432 |
| | 9 | December | 2222 | 2220 |
| | 10 | December | 23 | 10 |
| | 11 | December | 11 | 200 |
| | 12 | December | 11 | 1233 |
| | 13 | December | 3334 | 2121 |
| | 14 | December | 2121 | 2110 |
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| | 16 | December | 1012 | 2222 |
| | 17 | December | 2322 | 1120 |
| | 18 | December | 2002 | 1100 |
| | 19 | December | 10 | 1000 |
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| | 22 | December | 113 | 3003 |
| | 23 | December | 43 | 1213 |
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| | 28 | December | 1211 | 1111 |
| | 29 | December | 1100 | 110 |
| | 30 | December | 1334 | 3332 |
| | 31 | December | 1113 | 3322 |

| Year | Date | | K-index | |
|---|---|---|---|---|
| 1991 | 1 | January | 3112 | 1001 |
| | 2 | January | 1121 | 1011 |
| | 3 | January | 1212 | 3112 |
| | 4 | January | 2220 | 12 |
| | 5 | January | 2212 | 3121 |
| | 6 | January | 1112 | 1000 |
| | 7 | January | 1000 | 1 |
| | 8 | January | 2122 | 3221 |
| | 9 | January | 112 | 1022 |
| | 10 | January | 2122 | 2213 |
| | 11 | January | 22 | 2221 |
| | 12 | January | 4253 | 2422 |
| | 13 | January | 2211 | 2130 |
| | 14 | January | 1111 | 0 |
| | 15 | January | 2122 | 3133 |
| | 16 | January | 1022 | 3112 |
| | 17 | January | 2114 | 3322 |
| | 18 | January | 1221 | 2323 |
| | 19 | January | 101 | 10 |
| | 20 | January | 2 | 110 |
| | 21 | January | 111 | 2 |
| | 22 | January | 2211 | 1011 |
| | 23 | January | 122 | 1023 |
| | 24 | January | 3234 | 3443 |
| | 25 | January | 3333 | 3443 |
| | 26 | January | 2333 | 3113 |
| | 27 | January | 23 | 3223 |
| | 28 | January | 122 | 3111 |
| | 29 | January | 1112 | 1211 |
| | 30 | January | 100 | 1322 |
| | 31 | January | 3244 | 2333 |
| | | | | |
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| | 2 | February | 5321 | 1001 |
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| | 4 | February | 1 | 1013 |
| | 5 | February | 2132 | 2232 |
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| | 7 | February | 1212 | 2223 |
| | 8 | February | 2223 | 2322 |
| | 9 | February | 4113 | 2443 |
| | 10 | February | 3112 | 1111 |
| | 11 | February | 3222 | 1323 |
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| | 13 | February | 2204 | 3222 |
| | 14 | February | 1102 | 2323 |
| | 15 | February | 3012 | 2022 |
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| | 18 | February | 11 | 11 |
| | 19 | February | 2 | 4420 |
| | 20 | February | 1011 | 1243 |
| | 21 | February | 2223 | 1210 |
| | 22 | February | 1334 | 3222 |
| | 23 | February | 2233 | 3432 |
| | 24 | February | 1210 | 21 |
| | 25 | February | 1123 | 2221 |
| | 26 | February | 1133 | 2201 |
| | 27 | February | 23 | 2122 |
| | 28 | February | 3233 | 3223 |
| | | | | |
| | 1 | March | 3233 | 2134 |
| | 2 | March | 2223 | 2122 |
| | 3 | March | 2021 | 22 |
| | 4 | March | 1001 | 1332 |
| | 5 | March | 3244 | 3423 |
| | 6 | March | 2243 | 3354 |
| | 7 | March | 3323 | 3444 |
| | 8 | March | 3234 | 3324 |
| | 9 | March | 4434 | 4325 |
| | 10 | March | 4422 | 3010 |
| | 11 | March | 12 | 2001 |
| | 12 | March | 2233 | 3234 |
| | 13 | March | **6443** | 2310 |
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| | 17 | March | 2224 | 2133 |
| | 18 | March | 3333 | 0 |
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| | 20 | March | 3333 | 2121 |
| | 21 | March | 1144 | 5432 |
| | 22 | March | 2343 | 3224 |
| | 23 | March | 4323 | 3211 |
| | 24 | March | **2866** | **5378** |
| | 25 | March | **6643** | 4555 |
| | 26 | March | **6555** | **7443** |
| | 27 | March | 4543 | 3444 |
| | 28 | March | 4323 | 2331 |
| | 29 | March | 121 | 102 |
| | 30 | March | 1332 | 3334 |
| | 31 | March | 3222 | 12 |
| | | | | |
| | 1 | April | 4444 | 4334 |
| | 2 | April | 4334 | 2334 |
| | 3 | April | 4354 | 3344 |
| | 4 | April | **3236** | **6443** |
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| | 6 | April | 3323 | 1332 |
| | 7 | April | 2323 | 2122 |
| | 8 | April | 2011 | 1022 |
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| | 10 | April | 1122 | 2101 |
| | 11 | April | 1012 | 1110 |
| | 12 | April | 1233 | 3211 |
| | 13 | April | 122 | 1110 |
| | 14 | April | 1123 | 2121 |
| | 15 | April | 1023 | 2100 |
| | 16 | April | 2 | 1221 |

| | | | | |
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| | 18 | April | 1134 | 2132 |
| | 19 | April | 1344 | 1011 |
| | 20 | April | 11 | 1000 |
| | 21 | April | 1113 | 2111 |
| | 22 | April | 1023 | 2110 |
| | 23 | April | 3 | 2322 |
| | 24 | April | 2122 | 2034 |
| | 25 | April | 4334 | 2012 |
| | 26 | April | 3331 | 1113 |
| | 27 | April | 3433 | 3234 |
| | 28 | April | 4443 | 4344 |
| | 29 | April | **6444** | 4454 |
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| | | | | |
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| | 2 | May | 4443 | 4433 |
| | 3 | May | 2323 | 2123 |
| | 4 | May | 3110 | 1112 |
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| | 6 | May | 110 | 1003 |
| | 7 | May | 1133 | 1000 |
| | 8 | May | 2033 | 1220 |
| | 9 | May | 2122 | 2233 |
| | 10 | May | 1133 | 2202 |
| | 11 | May | 1012 | 100 |
| | 12 | May | 2 | 20 |
| | 13 | May | 135 | 3343 |
| | 14 | May | 245 | 3433 |
| | 15 | May | 1232 | 2000 |
| | 16 | May | 1001 | 2143 |
| | 17 | May | 4343 | 3310 |
| | 18 | May | 0 | 0 |
| | 19 | May | 1101 | 11 |
| | 20 | May | 11 | 1000 |
| | 21 | May | 2 | 3210 |
| | 22 | May | 3233 | 2122 |
| | 23 | May | 3334 | 4323 |
| | 24 | May | 3233 | 4344 |
| | 25 | May | 4423 | 2433 |
| | 26 | May | 2243 | 3444 |
| | 27 | May | 4334 | 4234 |
| | 28 | May | 4333 | 3344 |
| | 29 | May | 4333 | 3143 |
| | 30 | May | 3133 | 2323 |
| | 31 | May | 2134 | 5432 |
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| | 1 | June | 3355 | 5513 |
| | 2 | June | 4333 | **3546** |
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| | 4 | June | 1023 | **5655** |
| | 5 | June | **5767** | **5766** |
| | 6 | June | 5554 | 2104 |
| | 7 | June | 2244 | 2233 |
| | 8 | June | 2222 | 3452 |

| | | | | |
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| | 9 | June | **6334** | 3553 |
| | 10 | June | **4356** | **5456** |
| | 11 | June | **6544** | 4344 |
| | 12 | June | 4324 | 4444 |
| | 13 | June | **6566** | **6574** |
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| | 15 | June | 1243 | 2310 |
| | 16 | June | 1 | 1 |
| | 17 | June | 2214 | **5566** |
| | 18 | June | 3432 | 1243 |
| | 19 | June | 3444 | 3434 |
| | 20 | June | 4323 | 1132 |
| | 21 | June | 5233 | 2333 |
| | 22 | June | 3322 | 2223 |
| | 23 | June | 3335 | 4345 |
| | 24 | June | 5433 | 3233 |
| | 25 | June | 4324 | 2234 |
| | 26 | June | 4223 | 3333 |
| | 27 | June | 3112 | 113 |
| | 28 | June | 2321 | 11 |
| | 29 | June | 0 | 1011 |
| | 30 | June | 3323 | 2445 |
| | | | | |
| | 1 | July | 3320 | 2232 |
| | 2 | July | 133 | 3234 |
| | 3 | July | 3234 | 3233 |
| | 4 | July | 4222 | 2211 |
| | 5 | July | 11 | 1100 |
| | 6 | July | 1012 | 1222 |
| | 7 | July | 1200 | 1123 |
| | 8 | July | 3233 | **3565** |
| | 9 | July | **2376** | 5555 |
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| | 11 | July | 3234 | 3212 |
| | 12 | July | 2235 | 3332 |
| | 13 | July | **4456** | **5755** |
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| | 15 | July | 3322 | 1011 |
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| | 19 | July | 4434 | 4354 |
| | 20 | July | 3443 | 3333 |
| | 21 | July | 3433 | 3234 |
| | 22 | July | 3333 | 3224 |
| | 23 | July | 4222 | 3330 |
| | 24 | July | 1012 | 212 |
| | 25 | July | 1122 | 2221 |
| | 26 | July | 100 | 1 |
| | 27 | July | 1001 | 123 |
| | 28 | July | 1220 | 2 |
| | 29 | July | 1120 | 2 |
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| | 29 | August | 123 | 2323 |
| | 30 | August | 1223 | 4354 |
| | 31 | August | 2254 | 3334 |
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| | 7 | September | 3222 | 2111 |
| | 8 | September | 2222 | 3453 |
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| | 11 | September | 4224 | 3232 |
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| | 18 | September | 111 | 1012 |
| | 19 | September | 3213 | 3113 |
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| | 22 | September | 1012 | 2201 |
| | 23 | September | 1001 | 1 |

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| | 8 | October | 3243 | **3463** |
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| | 29 | October | **5664** | **4664** |
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| | 31 | October | 4255 | **3446** |
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| | 6 | November | 2332 | 2323 |
| | 7 | November | 3322 | 1222 |
| | 8 | November | 2255 | **7679** |
| | 9 | November | **7667** | 5544 |
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| | 13 | November | 1123 | 4423 |
| | 14 | November | 4322 | 4224 |
| | 15 | November | 3234 | 4434 |

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| | 16 | November | 4234 | 3333 |
| | 17 | November | 3334 | 3332 |
| | 18 | November | 3333 | 3343 |
| | 19 | November | 5344 | **4654** |
| | 20 | November | 1232 | 2444 |
| | 21 | November | 2344 | **4756** |
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| | 24 | November | 2221 | 2332 |
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| | 27 | November | 1011 | 222 |
| | 28 | November | 1012 | 2234 |
| | 29 | November | 3311 | 3223 |
| | 30 | November | 2222 | 2224 |
| | | | | |
| | 1 | December | 2222 | 2223 |
| | 2 | December | 3323 | 5333 |
| | 3 | December | 2223 | 3233 |
| | 4 | December | 3222 | 2233 |
| | 5 | December | 2201 | 1221 |
| | 6 | December | 2102 | 1001 |
| | 7 | December | 1111 | 1122 |
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| | 17 | December | 4344 | 4343 |
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| | 20 | December | 222 | 3332 |
| | 21 | December | 3344 | 3313 |
| | 22 | December | 2132 | 112 |
| | 23 | December | 2232 | 1122 |
| | 24 | December | 2323 | 2110 |
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| | 26 | December | 1222 | 2233 |
| | 27 | December | 5334 | 4554 |
| | 28 | December | 3113 | 4344 |
| | 29 | December | 5433 | 4445 |
| | 30 | December | 4333 | 4233 |
| | 31 | December | 3112 | 3323 |

| Year | Date | | K-index | |
|---|---|---|---|---|
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| | 2 | January | 5435 | 3331 |
| | 3 | January | 3213 | 2124 |
| | 4 | January | 3233 | 2133 |
| | 5 | January | 3222 | 2432 |
| | 6 | January | 2221 | 3333 |
| | 7 | January | 2202 | 2232 |
| | 8 | January | 3233 | 3232 |
| | 9 | January | 2200 | 2123 |
| | 10 | January | 3223 | 2223 |
| | 11 | January | 2213 | 3343 |
| | 12 | January | 3245 | 4442 |
| | 13 | January | 3333 | 3433 |
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| | 15 | January | 3233 | 4331 |
| | 16 | January | 1233 | 4344 |
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| | 19 | January | 1221 | 1201 |
| | 20 | January | 2223 | 3222 |
| | 21 | January | 1000 | 2223 |
| | 22 | January | 2122 | 2010 |
| | 23 | January | 22 | 1021 |
| | 24 | January | 1002 | 103 |
| | 25 | January | 2101 | 1001 |
| | 26 | January | 1 | 4423 |
| | 27 | January | 4434 | 2234 |
| | 28 | January | 2322 | 3332 |
| | 29 | January | 2232 | 3244 |
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| | | | | |
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| | 7 | February | 2234 | 3211 |
| | 8 | February | 3342 | **5745** |
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| | 15 | February | 122 | 2100 |
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| | 19 | February | 3233 | 3222 |
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| | 26 | February | 3343 | **4676** |
| | 27 | February | **6467** | 3553 |
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| | 29 | February | 2215 | 5543 |
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| | 3 | March | 2222 | 1221 |
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| | 14 | March | 1 | 111 |
| | 15 | March | 1133 | 2332 |
| | 16 | March | 1123 | 4342 |
| | 17 | March | 2015 | 4344 |
| | 18 | March | 4343 | 3211 |
| | 19 | March | 0 | 201 |
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| | 24 | March | 3423 | 3345 |
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| | 27 | March | 2110 | 1143 |
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| | 31 | March | 4213 | 2333 |
| | | | | |
| | 1 | April | 2323 | 2122 |
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| | 7 | April | 2343 | 3221 |
| | 8 | April | 3332 | 2241 |
| | 9 | April | 1111 | 2112 |
| | 10 | April | 1111 | 1110 |
| | 11 | April | 1100 | 0 |
| | 12 | April | 1111 | 1200 |
| | 13 | April | 132 | 1011 |
| | 14 | April | 21 | 122 |
| | 15 | April | 3223 | 1101 |

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|---|---|---|---|---|
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| | 17 | April | 0 | 202 |
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| | 19 | April | 4232 | 2334 |
| | 20 | April | 3322 | 3223 |
| | 21 | April | 3322 | 1100 |
| | 22 | April | 3223 | 2233 |
| | 23 | April | 2010 | 1322 |
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| | 25 | April | 2233 | 2113 |
| | 26 | April | 1022 | 1032 |
| | 27 | April | 2010 | 1132 |
| | 28 | April | 2123 | 2122 |
| | 29 | April | 2120 | 122 |
| | 30 | April | 2123 | 3101 |
| | | | | |
| | 1 | May | 1132 | 2342 |
| | 2 | May | 3231 | 1111 |
| | 3 | May | 2112 | 2222 |
| | 4 | May | 2412 | 2201 |
| | 5 | May | 202 | 111 |
| | 6 | May | 11 | 1112 |
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| | 8 | May | 1233 | 4444 |
| | 9 | May | 3302 | **3465** |
| | 10 | May | **4477** | **6666** |
| | 11 | May | **6532** | 4443 |
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| | 13 | May | 3423 | 3113 |
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| | 17 | May | 11 | 11 |
| | 18 | May | 1011 | 135 |
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| | 21 | May | 2021 | 23 |
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| | 23 | May | 2231 | 2351 |
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| | 27 | May | 1132 | 2211 |
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| | 29 | May | 2231 | 3332 |
| | 30 | May | 1121 | 3222 |
| | 31 | May | 3210 | 200 |
| | | | | |
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| | 3 | June | 1121 | 110 |
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| | 7 | June | 122 | 1143 |

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| | 8 | June | 5343 | **3446** |
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| | 10 | June | 1334 | 3322 |
| | 11 | June | 2312 | 2255 |
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| | 14 | June | 2011 | 112 |
| | 15 | June | 3320 | 2221 |
| | 16 | June | 1101 | 1000 |
| | 17 | June | 110 | 110 |
| | 18 | June | 1111 | **3365** |
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| | 20 | June | 1211 | 2101 |
| | 21 | June | 3100 | 102 |
| | 22 | June | 3202 | 2111 |
| | 23 | June | 2311 | 1233 |
| | 24 | June | 2333 | 2332 |
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| | 26 | June | 1021 | 2113 |
| | 27 | June | 1012 | 2122 |
| | 28 | June | 1244 | 2212 |
| | 29 | June | 3432 | 2444 |
| | 30 | June | 4443 | 2203 |
| | | | | |
| | 1 | July | 3322 | 2243 |
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| | 5 | July | 2202 | 2012 |
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| | 7 | July | 10 | 101 |
| | 8 | July | 0 | 1001 |
| | 9 | July | 1101 | 1101 |
| | 10 | July | 1210 | 10 |
| | 11 | July | 1010 | 0 |
| | 12 | July | 2222 | 3122 |
| | 13 | July | 1343 | 2333 |
| | 14 | July | 3323 | 1231 |
| | 15 | July | 2201 | 0 |
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| | 17 | July | 2100 | 1200 |
| | 18 | July | 101 | 1 |
| | 19 | July | 1020 | 11 |
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| | 21 | July | 122 | 2332 |
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| | 28 | July | 3432 | 1123 |
| | 29 | July | 0 | 1002 |
| | 30 | July | 3101 | 2032 |
| | 31 | July | 2022 | 1324 |

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| | 2 | August | 2 | 1121 |
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| | 4 | August | 3101 | 3444 |
| | 5 | August | 4444 | 3123 |
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| | 14 | August | 3212 | 2420 |
| | 15 | August | 2030 | 33 |
| | 16 | August | 1122 | 1001 |
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| | 19 | August | 111 | 1122 |
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| | 21 | August | 1212 | 2441 |
| | 22 | August | 1234 | 4455 |
| | 23 | August | **6762** | 3132 |
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| | 27 | August | 1223 | 3232 |
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| | 29 | August | 4323 | 2013 |
| | 30 | August | 1010 | 2021 |
| | 31 | August | 101 | 0 |
| | | | | |
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| | 3 | September | 3345 | 4454 |
| | 4 | September | 4343 | 3235 |
| | 5 | September | 4333 | 2233 |
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| | 17 | September | 4455 | **4576** |
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| | 19 | September | 3212 | 2231 |
| | 20 | September | 1122 | 2023 |
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| | 22 | September | 4422 | 1123 |

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| | 23 | September | 1213 | 121 |
| | 24 | September | 0 | 11 |
| | 25 | September | 2123 | 2233 |
| | 26 | September | 3200 | 1310 |
| | 27 | September | 12 | 2001 |
| | 28 | September | 22 | 3334 |
| | 29 | September | 3553 | 4434 |
| | 30 | September | 3333 | 4444 |
| | | | | |
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| | 3 | October | 10 | 11 |
| | 4 | October | 2322 | 2000 |
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| | 6 | October | 2212 | 2111 |
| | 7 | October | 1122 | 1121 |
| | 8 | October | 3111 | 133 |
| | 9 | October | **3336** | 3343 |
| | 10 | October | 233 | 2012 |
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| | 12 | October | 3334 | 5422 |
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| | 18 | October | 2011 | 1323 |
| | 19 | October | 4223 | 3323 |
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| | 21 | October | 1122 | 1212 |
| | 22 | October | 2112 | 3321 |
| | 23 | October | 1121 | 1002 |
| | 24 | October | 1100 | 2 |
| | 25 | October | 3122 | 1122 |
| | 26 | October | 3233 | 1233 |
| | 27 | October | 4333 | 2432 |
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| | 29 | October | 2333 | 2454 |
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| | 3 | November | 4333 | 3022 |
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| | 11 | November | 3324 | 2322 |
| | 12 | November | 3213 | 3234 |
| | 13 | November | 2224 | 4222 |
| | 14 | November | 1223 | 3232 |

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| | 15 | November | 2122 | 3434 |
| | 16 | November | 3220 | 1133 |
| | 17 | November | 2222 | 1122 |
| | 18 | November | 2012 | 1330 |
| | 19 | November | 123 | 2221 |
| | 20 | November | 1001 | 22 |
| | 21 | November | 3200 | 11 |
| | 22 | November | 1243 | 4333 |
| | 23 | November | 3533 | 4432 |
| | 24 | November | 2232 | 2332 |
| | 25 | November | 2133 | 3222 |
| | 26 | November | 2212 | 3012 |
| | 27 | November | 1111 | 2100 |
| | 28 | November | 1112 | 2121 |
| | 29 | November | 1122 | 3110 |
| | 30 | November | 23 | 2351 |
| | | | | |
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| | 2 | December | 3212 | 2222 |
| | 3 | December | 1303 | 3322 |
| | 4 | December | 1133 | 3223 |
| | 5 | December | 3211 | 100 |
| | 6 | December | 1001 | 1111 |
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| | 8 | December | 4323 | 3344 |
| | 9 | December | 3223 | 3323 |
| | 10 | December | 2224 | 1443 |
| | 11 | December | 2212 | 1222 |
| | 12 | December | 2211 | 2122 |
| | 13 | December | 3202 | 1211 |
| | 14 | December | 2111 | 2232 |
| | 15 | December | 3223 | 3133 |
| | 16 | December | 1222 | 0 |
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| | 19 | December | 1212 | 3244 |
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| | 21 | December | 1133 | 3442 |
| | 22 | December | 2122 | 3211 |
| | 23 | December | 1123 | 3221 |
| | 24 | December | 212 | 3231 |
| | 25 | December | 122 | 1222 |
| | 26 | December | 1001 | 111 |
| | 27 | December | 10 | 34 |
| | 28 | December | 3133 | **4655** |
| | 29 | December | 4333 | 3522 |
| | 30 | December | 2132 | 3211 |
| | 31 | December | 2132 | 3311 |

ESKOM Transmission Group

# TECHNOLOGY SERVICES DIVISION

# SUBSTATION ENGINEERING DEPARTMENT

# REPORT SE91/26

## Alpha and Beta 765kV Reactors Investigations and Recommendations

P V Goosen

R J C Moore

C E Odendaal

November 1991

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REPORT ON FAILURE INVESTIGATION

OF 765 KV REACTORS AT BETA SUBSTATION

CONTENTS PAGE




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## S U M M A R Y

The cause of failure of two 765 kV shunt reactors at Beta Subst has been investigated by ESKOM and Toshiba.

This report covers these investigations and recommends that all Toshiba reactors be brought to Rotek for modifications as per T recommendations

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## 1. BACKGROUND

Reactor No. 2 (Blue Phase Serial No. 85900082) failed on 18 April 1991. A Buchholz alarm was received approximately 1½ hours before failure occurred and the operator had requested National Control permission to switch out the reactor.

The reactor tripped on Buchholz and tank pressure protection. Tests carried out on site indicated failure and the unit was brought to Rotek for repair.

Reactor No. 2 (Red Phase Serial No. 85900002) was removed from service on 23 September 1991 approximately 1 hour after a Buchholz alarm. Oil testing of hydro carbon gases indicated overheating.

## 2. ADDITIONAL INFORMATION RECEIVED FROM SITE

According to site measurements no abnormal voltage conditions were recorded on the system prior to the faults nor at any previous occasion.

It was reported that the neutral earthing reactors on each three phase reactor bank had faulted during the past twelve months.

There were also reports of a high temperature alarm received on the Alpha 2 reactor on 30 January 1991.

## 3. INSPECTION AT ROTEK

REACTOR SE. NO. 85900082

The following observations were made :

3.1 The windings near the top of the coil were severely twisted and bent. Flash marks were evident on the copper conductors.

3.2 The upper yoke was damaged at two places where overheating of the laminations had occurred to the extent that they had melted leaving cavities measuring approximately 100 x 50 mm

3.3 The upper shunts controlling the leakage flux from the winding returning to the yokes showed signs of overheating. The shunt insulation had also deteriorated.

3.4 At the tips of three upper magnetic shunts on the line side, a number of laminations had spread open and bent towards the yoke. They had penetrated the insulation causing electrical contact. The yoke laminations had melted at these points.

3.5 Molten metal particles from the yoke laminations were found between some of the winding conductors.

3.6 The top wooden clamping ring was broken and showed signs of electrical tracking.

3.7 The oil had discoloured.

3.8 The lower magnetic shunts were slightly discoloured, but appeared normal.

REACTOR SE. NO. 85900002 ETA 11

The following observations were made :

3.9 There was no apparent damage to the winding.

3.10 The winding insulation was contaminated with carbon deposits.

3.11 The upper yoke was damaged at two places where overheating and deterioration of the insulation had occurred.

3.12 The upper shunts controlling the leakage flux showed signs of overheating.

3.13 At the tips of three upper magnetic shunts on the line side, a number of laminations had spread open and bent towards the yoke. One shunt on the neutral side had bent in a similar manner. They had penetrated the insulation causing electrical contact. The yoke laminations had showed signs of overheating at these points.

3.14 The lower magnetic shunts were slightly discoloured, but appeared normal.

FAULT SCENARIO

REACTOR SE. NO. 85900082

From the available evidence the mode of failure is as follows :

The shunts collecting the stray flux from the winding situated at th top neutral end of the winding overheated due to a high flux density This region also corresponds to the highest oil temperature at the top of the winding. This caused the glue between laminations to fai allowing a number of laminations to bend towards the yoke as a resul of magnetic forces. In the process they pressed their way through the insulation and made electrical contact with the yoke. This in turn set up local circulating currents which overheated and melted the yoke laminations at the points of contact. Molten metal droppe onto the windings causing interturn short circuits resulting in tot winding failure.

REACTOR SE. NO. 85900002

A similar process had developed with this reactor resulting in yoke damage when the shunts bent to make electrical contact. There was evidence of local overheating, but melting had not occurred. Gas fr the faults tripped the reactor by Buchholz protection.

## RECOMMENDATIONS

PART A: TECHNICAL

1. IT IS RECOMMENDED THAT TOSHIBA'S PROPOSALS FOR REFURBISHMENT AND IMPROVEMENT OF THE EIGHT UNITS ON SITE AT BETA BE IMPLEMENTED WITHOUT CHANGES.

   These are applicable to all operating reactors at Beta:

   1.1 Remove reactor to Rotek

   1.2 Untank and remove winding (1st three under Toshiba supervision)

   1.3 Execute modifications around upper and lower magnetic shunts as per Toshiba improved design.

   1.4 Re-install original lower shunts

   1.5 Install winding

   1.6 Install new horizontally-stacked shunts ex Toshiba (original design) to replace thermally damaged units.

   1.7 Vapour phase

   1.8 Transport to BBT Pretoria and test as per Toshiba recommendations.

   1.9 Transport to Beta and re-install and commission.

2. SOURCE NEW REACTOR WINDING AS PER TOSHIBA ORIGINAL DESIGN FROM BBT/PRETORIA OR TOSHIBA/JAPAN AND REPAIR IMPROVE PROCESS AND TEST FIRST FAILED REACTOR AS PER ABOVE.

3. REPAIR SECOND FAILED REACTOR AS PER TOSHIBA RECOMMENDATIONS AND IMPROVE AS ABOVE.

4. REFILL ALL BETA REACTORS WITH NEW VIRGIN OIL. (8 X 30 KL)

5. IMPROVE REACTOR COOLING WITH THE ADDITION OF FORCED AIR COOLING AS PER TOSHIBA'S RECOMMENDATION TO REDUCE THE OPERATING TEMPERATURE BY APPROXIMATELY 15 DEG CELSIUS.

PART B: OPERATIONAL

1. Operate the 765 kV system with a nominal target voltage of 765 kV.

2. Install protection to avoid overfluxing of reactors due temporary over voltages (eg 10 minutes @ 1.05 pu of 800 kV)

3. Modify the alarm functions of Buchholz relays on all 765 kV reactors and transformers to initiate trips and configure the tripping logic appropriately to avoid consequential overvoltages following such tripping.

4. Convert **BOTH** 765 kV lines to 400 kV operation in order to facilitate the expeditious modification to all reactors in a target time of 12 months (subject to confirmation) without complex operating restrictions

PART C: PURCHASE OF BBT SPARE REACTORS

1. Proceed with purchase of two units from BBT

PART D: NEGOTIATIONS WITH TOSHIBA

1. Ratify verbal approval given to Toshiba to proceed with immediate manufacture of replacement shunts.

2. COST SHARING ESKOM/TOSHIBA

2.1 Negotiate for free delivery of all Toshiba repair/replacement/improvement material to Rotek.

2.2 Negotiate best price for one replacement winding required for repair of first faulted reactor.
(BBT or Toshiba)

2.3 Negotiate for free Toshiba quality control on winding if supplied by BBT/Pretoria.

2.4 Negotiate for free supervision of repair/refurbishment of first three reactors with training being transferred to nominated Rotek personnel.

2.5 We recommend that Eskom pay all transport, testing, workshop and re-installation and recommissioning costs

2.6 Negotiate for 50% sharing of cost for the supply of forced air cooling equipment and fittings to Beta site with installation and commissioning at Eskom's cost.

2.7 Risks of equipment damage during refurbishment/repair actions to be carried by Eskom.

2.8 Cost of new oil to be carried by Eskom.

PART E: ALPHA SUBSTATION REACTOR PROBLEM

1. Negotiate with Fuji to obtain technical details of internal designs to evaluate gassing problem.

2. Transport worst case Fuji Reactor to Rotek for inspection in January 1992.

3. Negotiate with Fuji to have designers available at Rotek for inspection in February 1992.

4. Treat other Fuji reactors at Alpha subject to findings.

PART F: VISIT TO TOSHIBA AND FUJI/JAPAN

It is recommended that a combined technical and commercial team be sent to Japan in January 1992 for negotiating with Toshiba and conducting technical discussions with Fuji.

PART G: PROJECT ESTABLISHMENT

In view of the importance, magnitude and logistics involved in executing the above recommendations (+/- R 15m), it is recommended that a project complete with vote and budget be established and a formal Project Leader be appointed.

COSTS AND TIME SCHEDULES

These are being prepared by Rotek.

ESTIMATED COSTS OF REPAIRS FOR SERIAL NO. 85900002

| | | (RAND) |
|---|---|---|
| Dismantle (Beta) | | 150 000 |
| Transport Beta - Rotek | | 43 000 |
| Rotek workshop charges<br>Rotek labour charges | ]<br>] | 592 000 |
| Transport (Rotek - BBT) | | 18 000 |
| BBT Testing | | 60 000 |
| Transport (BBT - Beta) | | 43 000 |
| Installation charges | | 190 000 |
| Filling of new oil (30 kl) | | 43 000 |
| Recommissioning charges | | 13 000 |
| Toshiba Materials | | (To be negotiated) |
| Toshiba supervision (first 3 units only) | | 70 000 |
| Supply of cooling fans<br>Installation of cooling fans | ]<br>] | 120 000 |
| Substation Technology Technical Supervision (One man month per reactor) | | 8 000 |
| TOTAL | | 1 350 000 |

APPENDIX D

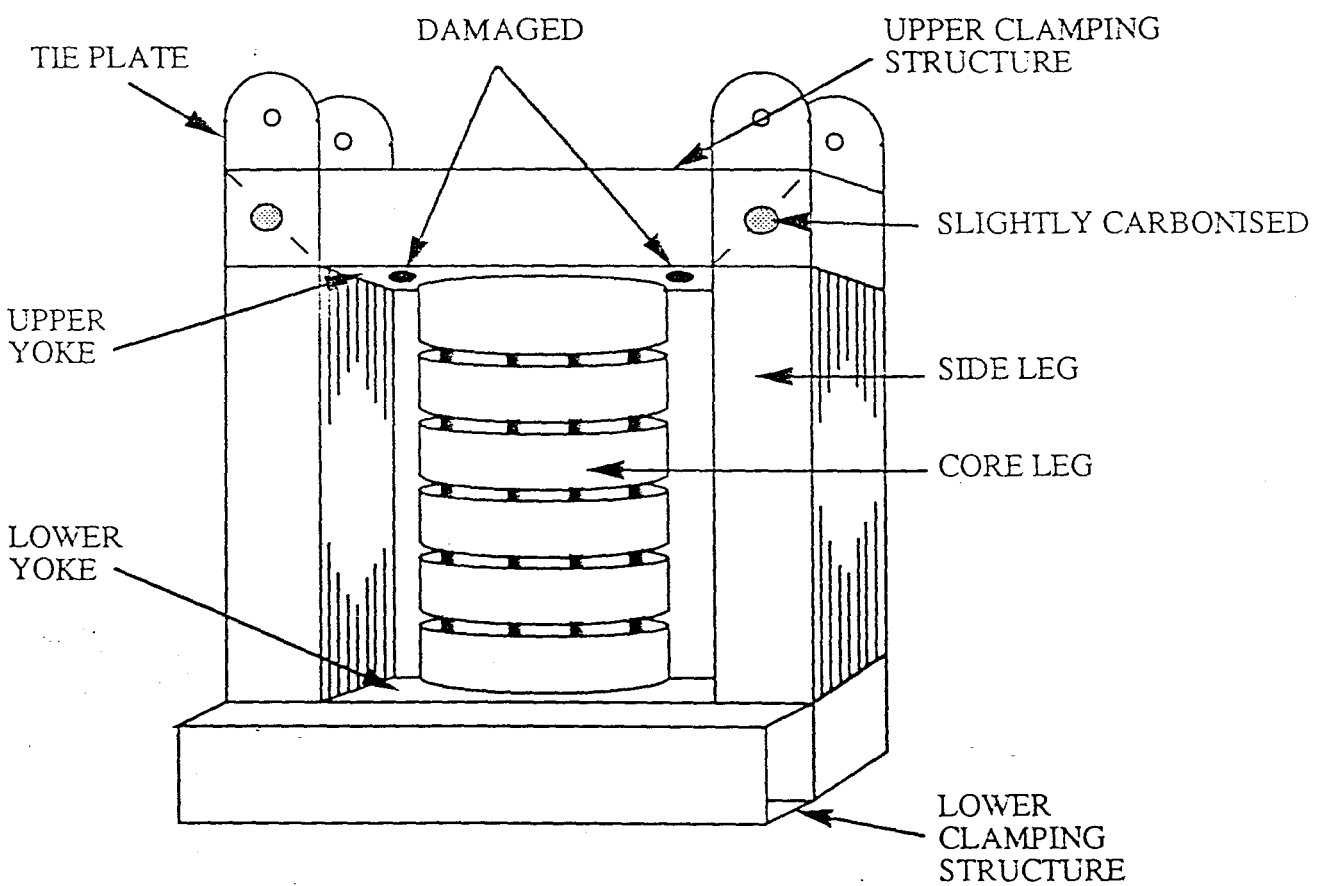
ESTIMATED COSTS OF REPAIRS FOR REMAINING UNITS AT BETA

ESTIMATED COST PER SINGLE PHASE UNIT (FOR EIGHT UNITS)

| | | (RAND) |
|---|---|---|
| Dismantle (Beta) | | 150 000 |
| Transport Beta - Rotek | | 43 000 |
| Rotek workshop charges<br>Rotek labour charges | ]<br>] | 375 000 |
| Transport (Rotek - BBT) | | 18 000 |
| BBT Testing | | 60 000 |
| Transport (BBT - Beta) | | 43 000 |
| Installation charges | | 190 000 |
| Filling of new oil (30 kl) | | 43 000 |
| Recommissioning charges | | 13 000 |
| Toshiba Materials | | (To be negotiated) |
| Toshiba supervision (first 3 units only) | | 70 000 |
| Supply of cooling fans<br>Installation of cooling fans | ]<br>] | 120 000 |
| Substation Technology Technical Supervision (One man month per reactor) | | 5 000 |
| | TOTAL | 1 130 000 |

APPENDIX 1

## CORE CLAMPING CONSTRUCTION



# A P P E N D I X 2

TEST ITEM

1. MEASUREMENT OF WINDING RESISTANCE

2. MEASUREMENT OF REACTANCE (ABOVE 2000)

3. DIELECTRIC LOSS ANGLE (tan δ) TEST (including capacitance)

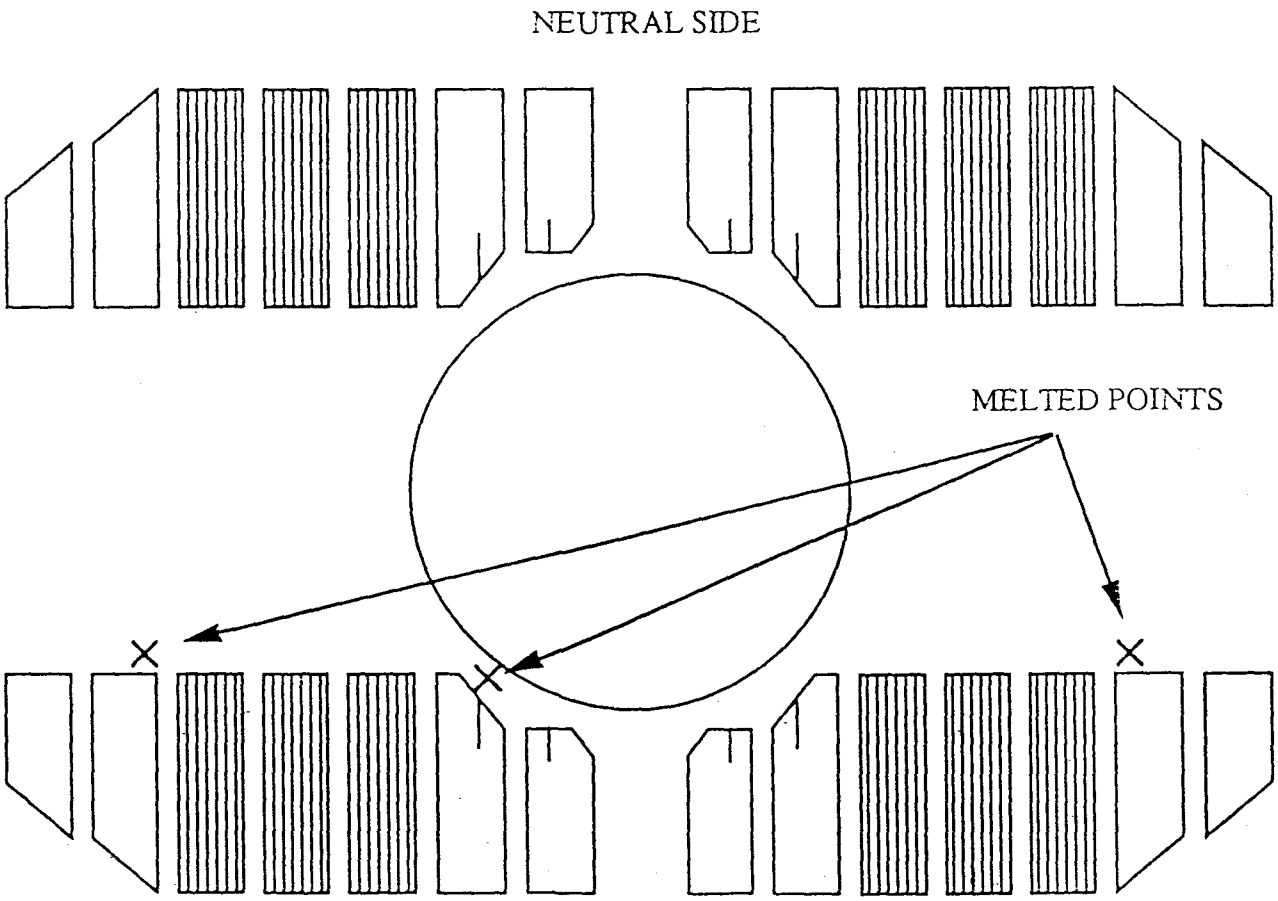
4. SEPARATE SOURCE VOLTAGE WITHSTAND TEST ACCORDING TO IEC REDUCED VOLTAGE (95 kV x 0.8)

5. IMPULSE VOLTAGE WITHSTAND TEST
   1950 kV x 0.8

6. SWITCHING IMPULSE VOLTAGE WITHSTAND TEST
   1425 kV x 0.8

APPENDIX 3

## UPPER MAGNETIC SHUNT



APPENDIX IV

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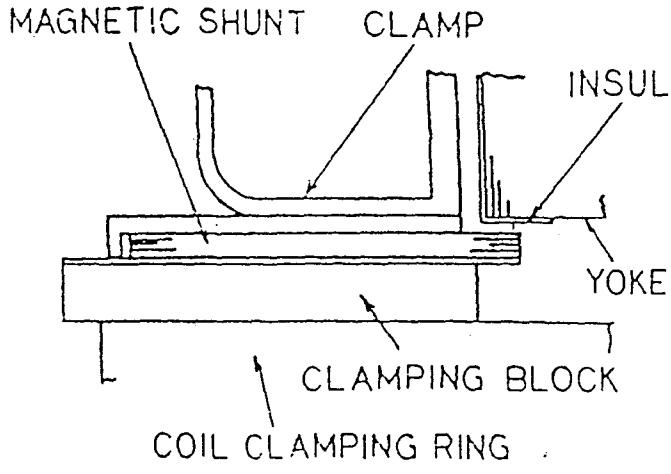
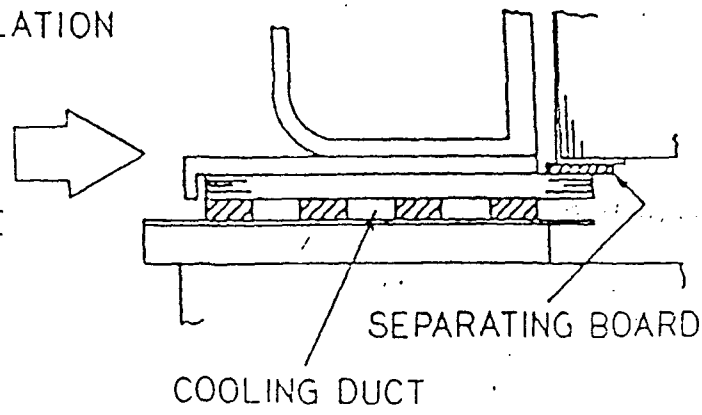
# CLAMP CONSTRUCTION

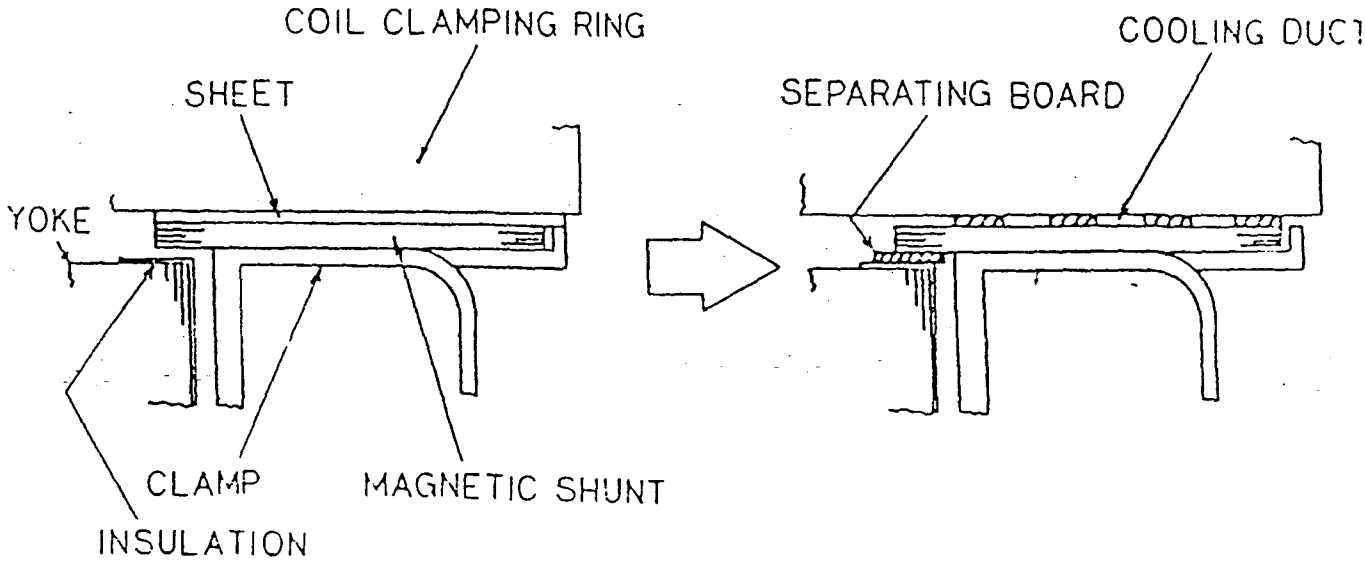
## EXISTING CONSTRUCTION



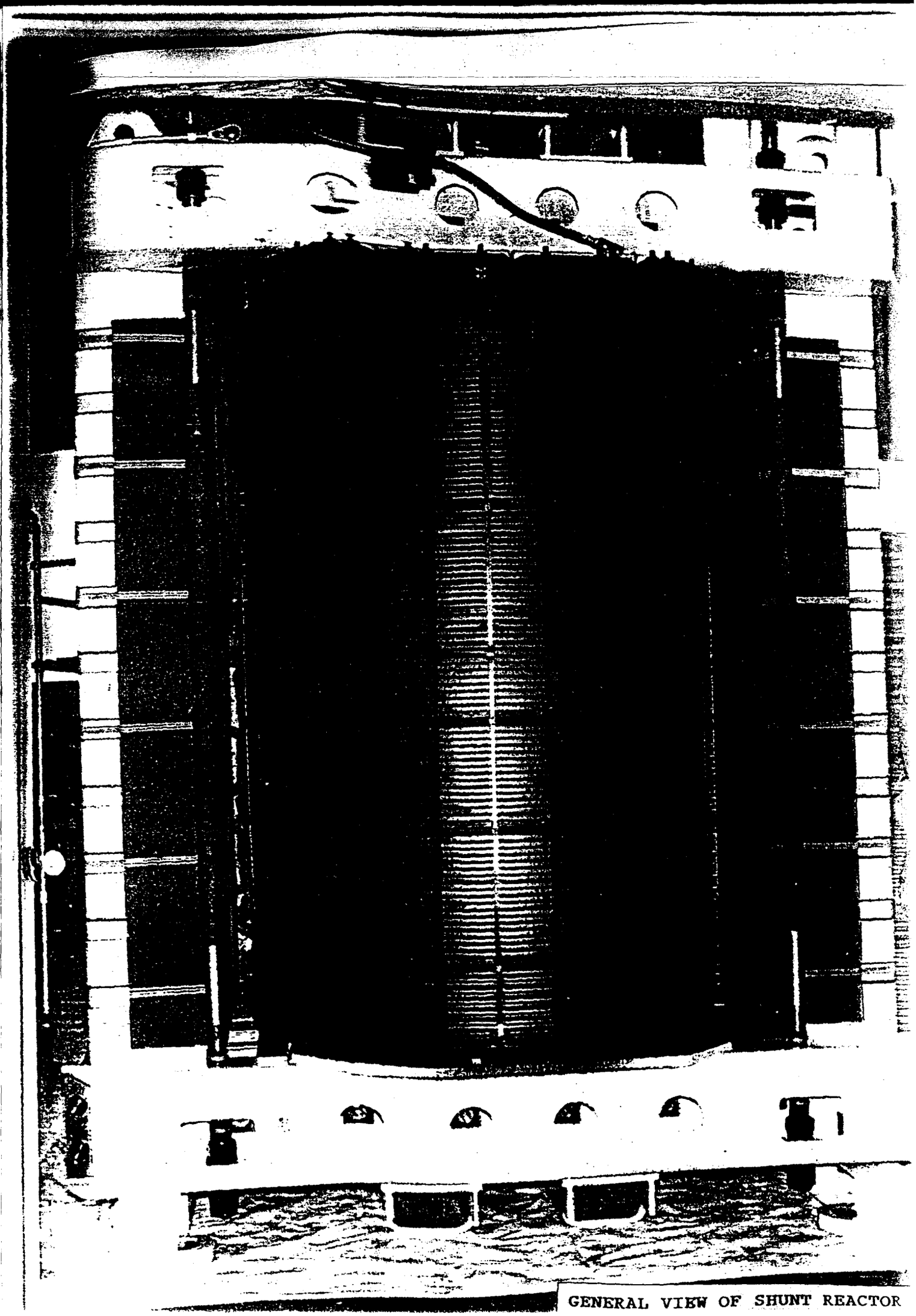

## NEW CONSTRUCTION



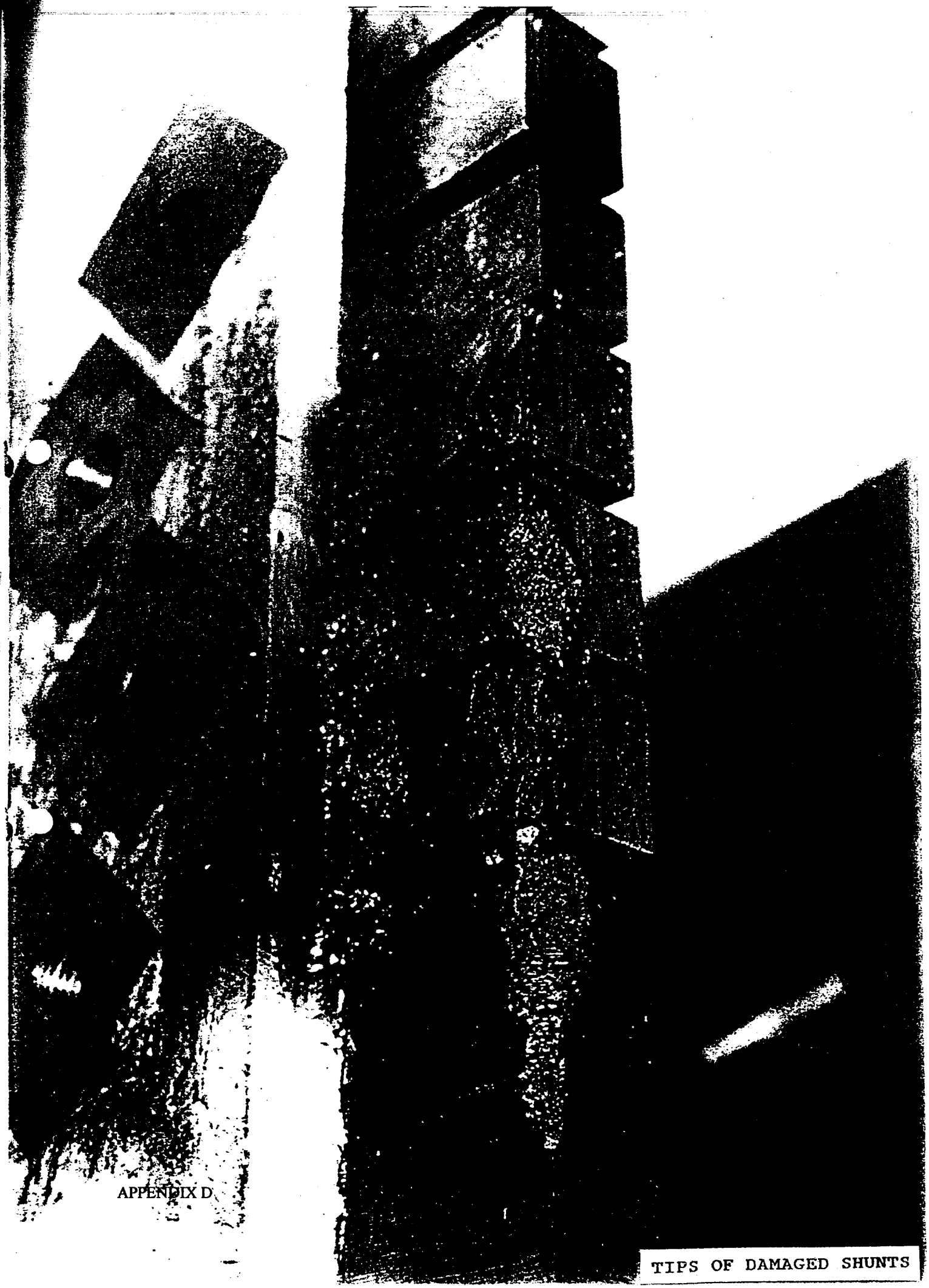

## UPPER SIDE




## LOWER SIDE.

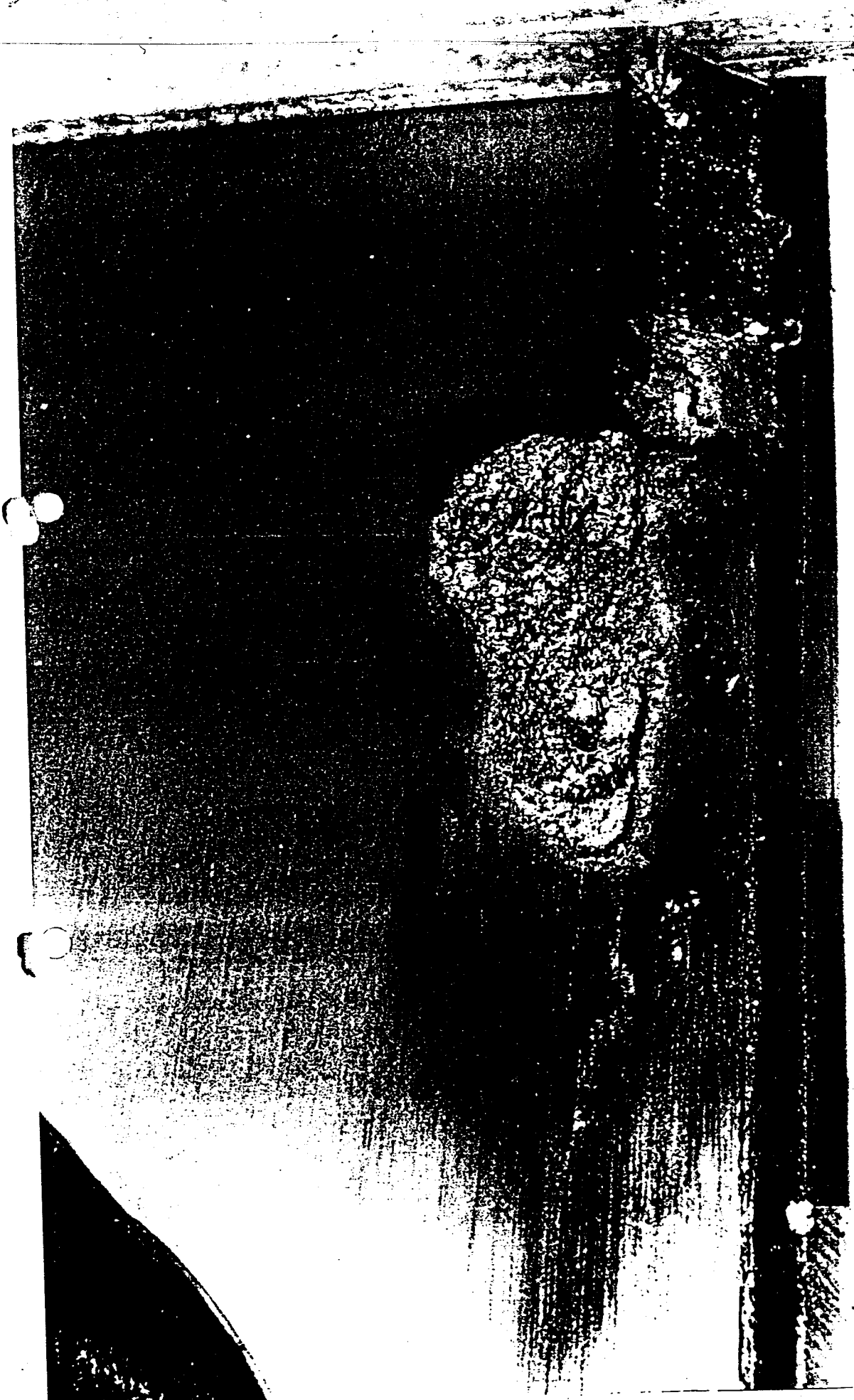


GENERAL VIEW OF SHUNT REACTOR

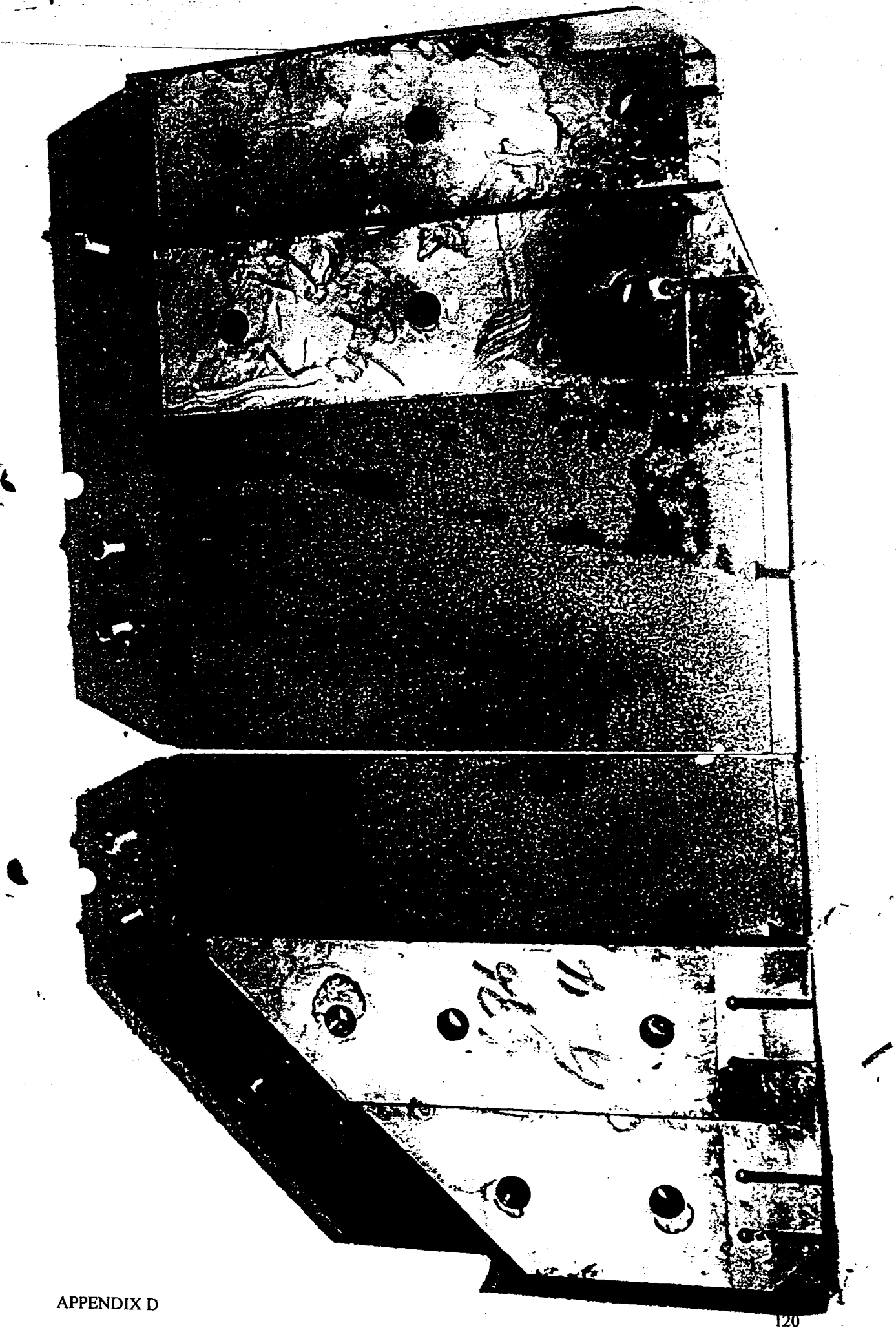


APPENDIX D

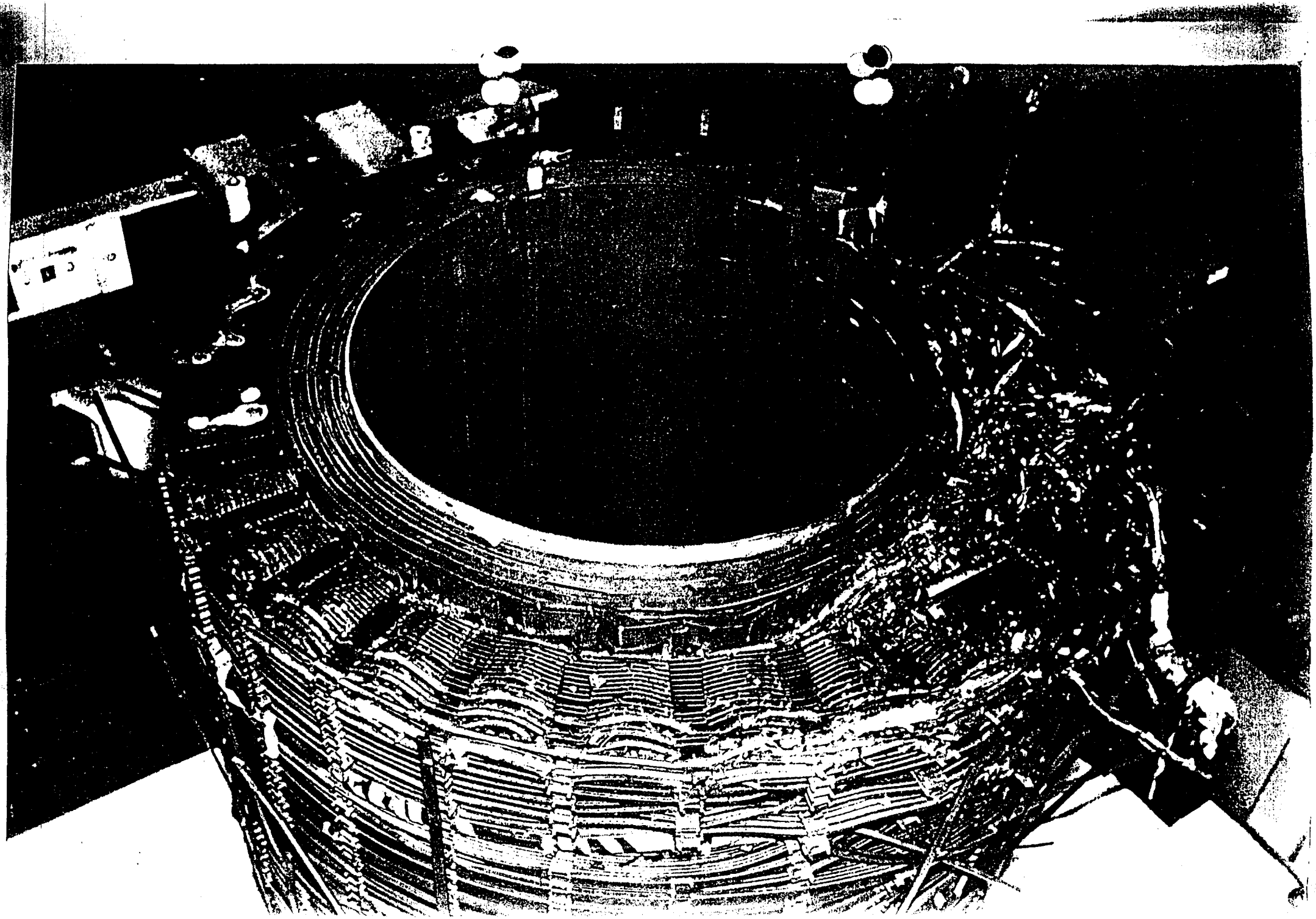
TIPS OF DAMAGED SHUNTS



POINT OF SHUNT CONTACT TO YOK
SHOWING OVERHEATING AND DAMAG
INSULATION



APPENDIX D



# APPENDIX E:

## CALCULATING THE ELECTRIC FIELD

The following calculation is a simplified example to illustrate the use of the equations in section 4.3. This procedure to calculate the electric field has been derived by Viljanen and Pirjola [68]. The earth is described as a half-space with a constant conductivity of $\sigma$ and the geomagnetic field propagates as a vertical plane wave in the earth. Using Cartesian co-ordinates, the x-axis is directed to the magnetic north, y to the magnetic east and z downwards. The electric field is then obtained by

$$E(T_N) = \frac{2}{\sqrt{\pi \mu_0 \sigma \Delta}} \left( R_{N-1} - R_N - \sqrt{M}\, b_{N-M} \right) \quad \ldots(1)$$

where $\Delta$ is the sampling interval, N is the sample number, M = 10 [66] and

$$R_N = \sum_{n=N-M+1}^{N} b_n \sqrt{N-n+1} \quad \ldots(2)$$

where bn = Bn – Bn-1 (B being the magnetic component).

Since magnetic and electric fields are perpendicular, $E_x$ will be calculated from $B_y$ and $E_y$ from $B_x$. This calculation was done to obtain the eastern electric field ($E_y$) from data on the northern magnetic field ($B_x$) as found in table 2 (none real values are used to simplify the example).

**Table E1** Five samples of northern magnetic field.

| **N** | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| **$B_x$ [nT]** | 300 | 320 | 290 | 300 | 330 |

The following assumptions and constants are used:

N = 5 (sampling number),

$\sigma$ = 0.001 (conductivity, i.e. $\rho$ = 1000 $\Omega$.m),

$\mu_0 = 4\pi * 10^{-7}$ (vacuum permeability),

$\Delta$ = 10 s (sampling interval), and,

M = 3 (M=3 to simplify the calculation, normally M = 10).

Then:

$$E(T_5) = \frac{2}{\sqrt{\Pi \mu_0 \sigma \Delta}} (R_4 - R_5 - \sqrt{3} b_2)$$

$$b_2 = B_2 - B_1 = 20 \times 10^{-9} T$$

$$R_4 = \sum_{n=4-3+1}^{4} b_n \sqrt{4-n+1}$$

$$R_4 = b_2\sqrt{3} + b_3\sqrt{2} + b_4\sqrt{1} = 2.215 \times 10^{-9}$$

$$similary \quad R_5 = -7.819 \times 10^{-9}$$

$$E_y(T_5) = 10066 \times (R_4 - R_5 - \sqrt{3} b_2) = -0.25 V/km$$

# APPENDIX F

## Magnetic Data Used for Example in Chapter 4

| Sample | $B_x$ [nT] | $dB_x/dt$ [nT/min] | $E_y$ [V/km] | $B_y$ [nT] | $dB_y/dt$ [nT/min] | $E_x$ [V/km] | $I_{gic} = aE_x+bE_y$ [A] |
|---|---|---|---|---|---|---|---|
| 0 | 9846 | | | -4325 | | | |
| 1 | 9854 | 4 | -0.009 | -4332 | -4 | **0.033** | -4 |
| 2 | 9856 | 1 | 0.024 | -4337 | -3 | **0.019** | -8 |
| 3 | 9865 | 4 | -0.051 | -4339 | -1 | **0.033** | 5 |
| 4 | 9877 | 6 | -0.059 | -4345 | -3 | **0.034** | 6 |
| 5 | 9892 | 7 | -0.069 | -4350 | -3 | **0.032** | 8 |
| 6 | 9880 | -6 | -0.013 | -4342 | 4 | **-0.006** | 4 |
| 7 | 9866 | -7 | 0.024 | -4339 | 2 | **-0.012** | -3 |
| 8 | 9854 | -6 | 0.046 | -4329 | 5 | **-0.030** | -4 |
| 9 | 9851 | -2 | 0.030 | -4325 | 2 | **-0.028** | -1 |
| 10 | 9852 | 1 | 0.025 | -4317 | 4 | **-0.048** | 3 |
| 11 | 9854 | 1 | 0.029 | -4308 | 4 | **-0.052** | 3 |
| 12 | 9842 | -6 | 0.042 | -4284 | 12 | **-0.101** | 8 |
| 13 | 9842 | 0 | 0.004 | -4258 | 13 | **-0.116** | 18 |
| 14 | 9843 | 0 | 0.015 | -4249 | 5 | **-0.089** | 12 |
| 15 | 9852 | 5 | -0.034 | -4239 | 5 | **-0.085** | 20 |
| 16 | 9866 | 7 | -0.047 | -4242 | -1 | **-0.050** | 17 |
| 17 | 9867 | 1 | -0.018 | -4243 | -1 | **-0.024** | 8 |
| 18 | 9872 | 3 | -0.042 | -4245 | -1 | **-0.007** | 9 |
| 19 | 9880 | 4 | -0.044 | -4245 | 0 | **-0.014** | 11 |
| 20 | 9847 | -16 | 0.074 | -4226 | 10 | **-0.049** | -7 |
| 21 | 9843 | -2 | 0.025 | -4218 | 4 | **-0.031** | 0 |
| 22 | 9852 | 4 | -0.001 | -4227 | -5 | **0.004** | -1 |
| 23 | 9866 | 7 | -0.034 | -4271 | -22 | **0.145** | -17 |
| 24 | 9901 | 18 | -0.103 | -4329 | -29 | **0.206** | -13 |
| 25 | 9936 | 17 | -0.137 | -4384 | -28 | **0.279** | -18 |
| 26 | 9956 | 10 | -0.165 | -4427 | -21 | **0.280** | -13 |
| 27 | 9952 | -2 | -0.063 | -4448 | -11 | **0.235** | -26 |
| 28 | 9984 | 16 | -0.167 | -4453 | -3 | **0.143** | 10 |
| 29 | 10003 | 10 | -0.139 | -4442 | 6 | **0.035** | 22 |
| 30 | 9971 | -16 | 0.035 | -4390 | 26 | **-0.117** | 12 |
| 31 | 10065 | 47 | -0.307 | -4374 | 8 | **-0.080** | 74 |
| 32 | 10041 | -12 | -0.033 | -4373 | 1 | **-0.081** | 20 |
| 33 | 9958 | -41 | 0.209 | -4354 | 9 | **-0.112** | -23 |
| 34 | 9931 | -14 | 0.108 | -4338 | 8 | **-0.115** | -3 |
| 35 | 9957 | 13 | -0.027 | -4343 | -2 | **-0.025** | 10 |
| 36 | 10081 | 62 | -0.312 | -4358 | -8 | **0.000** | 62 |
| 37 | 10001 | -40 | 0.158 | -4337 | 10 | **-0.080** | -18 |
| 38 | 9979 | -11 | 0.031 | -4278 | 30 | **-0.202** | 27 |
| 39 | 9954 | -12 | 0.075 | -4202 | 38 | **-0.313** | 36 |
| 40 | 9916 | -19 | 0.152 | -4176 | 13 | **-0.192** | 1 |
| 41 | 9921 | 2 | 0.110 | -4172 | 2 | **-0.163** | 5 |
| 42 | 9897 | -12 | 0.127 | -4140 | 16 | **-0.213** | 9 |
| 43 | 9872 | -12 | 0.185 | -4113 | 14 | **-0.181** | -7 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 44 | 9789 | -41 | 0.271 | -4013 | 50 | **-0.372** | 7 |
| 45 | 9777 | -6 | 0.160 | -4001 | 6 | **-0.156** | -6 |
| 46 | 9773 | -2 | 0.166 | -4039 | -19 | **-0.008** | -32 |
| 47 | 9843 | 35 | -0.163 | -4108 | -34 | **0.142** | 9 |
| 48 | 9871 | 14 | -0.067 | -4126 | -9 | **0.081** | 0 |
| 49 | 9850 | -11 | -0.026 | -4143 | -8 | **0.150** | -19 |
| 50 | 9860 | 5 | -0.078 | -4119 | 12 | **0.050** | 7 |
| 51 | 9824 | -18 | 0.052 | -4091 | 14 | **-0.036** | -4 |
| 52 | 9800 | -12 | 0.106 | -4091 | 0 | **-0.018** | -18 |
| 53 | 9784 | -8 | 0.105 | -4104 | -6 | **0.016** | -23 |
| 54 | 9781 | -2 | 0.073 | -4123 | -9 | **0.060** | -24 |
| 55 | 9751 | -15 | 0.133 | -4153 | -15 | **0.096** | -42 |
| 56 | 9735 | -8 | 0.111 | -4169 | -8 | **0.116** | -41 |
| 57 | 9733 | -1 | 0.067 | -4173 | -2 | **0.086** | -27 |
| 58 | 9725 | -4 | 0.057 | -4192 | -10 | **0.110** | -29 |
| 59 | 9720 | -3 | 0.059 | -4199 | -3 | **0.067** | -23 |
| 60 | 9717 | -1 | 0.035 | -4201 | -1 | **0.048** | -15 |
| 61 | 9707 | -5 | 0.049 | -4209 | -4 | **0.049** | -18 |
| 62 | 9695 | -6 | 0.065 | -4219 | -5 | **0.065** | -24 |
| 63 | 9683 | -6 | 0.059 | -4231 | -6 | **0.064** | -22 |
| 64 | 9673 | -5 | 0.061 | -4249 | -9 | **0.094** | -27 |
| 65 | 9678 | 3 | 0.022 | -4270 | -10 | **0.108** | -22 |
| 66 | 9671 | -4 | 0.046 | -4301 | -15 | **0.155** | -34 |
| 67 | 9676 | 3 | -0.005 | -4334 | -16 | **0.172** | -27 |
| 68 | 9702 | 13 | -0.074 | -4339 | -3 | **0.108** | -3 |
| 69 | 9710 | 4 | -0.048 | -4327 | 6 | **0.038** | 3 |
| 70 | 9699 | -5 | 0.002 | -4320 | 4 | **0.020** | -4 |
| 71 | 9683 | -8 | 0.029 | -4314 | 3 | **0.002** | -6 |
| 72 | 9691 | 4 | -0.028 | -4332 | -9 | **0.041** | -1 |
| 73 | 9793 | 51 | -0.301 | -4356 | -12 | **0.092** | 45 |
| 74 | 9803 | 5 | -0.097 | -4362 | -3 | **0.054** | 11 |
| 75 | 9824 | 10 | -0.181 | -4368 | -3 | **0.056** | 27 |
| 76 | 9863 | 19 | -0.239 | -4371 | -2 | **0.048** | 39 |
| 77 | 9872 | 4 | -0.131 | -4344 | 13 | **-0.071** | 38 |
| 78 | 9820 | -26 | 0.063 | -4317 | 14 | **-0.095** | 3 |
| 79 | 9821 | 0 | 0.004 | -4300 | 8 | **-0.092** | 14 |
| 80 | 9829 | 4 | -0.009 | -4306 | -3 | **-0.039** | 8 |
| 81 | 9838 | 5 | -0.008 | -4313 | -3 | **-0.035** | 7 |
| 82 | 9854 | 8 | -0.021 | -4310 | 1 | **-0.036** | 10 |
| 83 | 9859 | 3 | -0.055 | -4283 | 13 | **-0.082** | 24 |
| 84 | 9872 | 6 | -0.085 | -4257 | 13 | **-0.097** | 33 |
| 85 | 9875 | 2 | -0.045 | -4247 | 5 | **-0.085** | 23 |
| 86 | 9850 | -13 | 0.044 | -4250 | -2 | **-0.050** | -1 |
| 87 | 9841 | -5 | 0.053 | -4242 | 4 | **-0.063** | 0 |
| 88 | 9828 | -7 | 0.050 | -4241 | 1 | **-0.029** | -5 |
| 89 | 9824 | -2 | 0.059 | -4247 | -3 | **0.009** | -13 |
| 90 | 9821 | -2 | 0.046 | -4245 | 1 | **-0.007** | -8 |